Mathematical modelling of the process of crest formation by the working body of the cultivator – dump type

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Abstract. The results of theoretical studies of the cultivator - dump type ridger are presented. The analysis of the forces acting on the working body is carried out. An expression is obtained for determining the second consumption of soil mass transported by a working body. The rational parameters of the working body are determined.

1. Introduction
When cultivating row crops, such as corn, mechanical interrow cultivation is widely used [1], as one of the most effective and environmental methods of controlling weed vegetation [2].

The complexity of this method lies in the need for the simultaneous cutting and destruction of at least 95% of weeds in the immediate vicinity of cultivated plants and hilling (creation of a ridge) to ensure their reliable nutrition [3].

2. Model
The process of creating ridges is complex and multifactorial and it is directly affected by the following parameters: the speed of the machine-tractor aggregate (MTA), the size, shape and material of the working body, the mechanical composition of the soil, its physical properties, moisture, etc. [4].

We proposed a scheme of the working body of a ridge-forming cultivator of the cultivator-dump type, which provides simultaneous high-quality cutting of weeds and hilling of plants (ridge formation) in accordance with the agrotechnical requirements for row spacing to ensure high-quality and efficient implementation of the technological process of ridge formation during row-spacing processing (figure 1) [5].
The principle of operation of the proposed working body is as follows: the working body is installed in the row-spacing and installed at a predetermined depth of processing, then it starts to move under the action of the MTA traction, the soil in the central part of the row-spacings is cut by the lancet paw 1 and chisel 4, while partially shifted by the lancet paw to the periphery of the row-spacings. Dumps fixed at the ends of paws 2 cut the top layer of soil and form a ridge in the immediate vicinity of cultivated plants, hilling plants.

Qualitative indicators of the execution of operations depend on the design parameters of the working body (figure 2) and the rational choice of its operating modes, such as: \( v_s \) - MTA speed, m/s; \( d \) - depth of tillage, m; \( b, d, c \) - geometric parameters of the paws, m; \( r \) is the radius of the screw, which is the generatrix of the blade, m; \( h \) is the width of the blade, m; \( \phi \) is the elevation angle of the helix (screw) forming the blade, deg; \( \Psi \) is the angle of elevation of the axis of the screw to the surface of the soil forming the blade, deg; \( L \) is the length of the helix forming the blade, m; \( \sigma \) is the angle of the circular segment bounded by the blade, deg.

![Figure 1](image1.png)

**Figure 1.** General view of the working body of the cultivator-dump type ridger: 1 - lancet paw; 2 - dump; 3 - rack; 4 - chisel.

![Figure 2](image2.png)

**Figure 2.** The experimental design of working body of the cultivator-dump type ridger: a – general view; b – rear view; c – in-side view; d – dump scheme.
In order to create a mathematical model of the interaction of the working body with the soil, it is necessary to take into account the forces (figure 3) acting on it [6]:

- \( F_I \) – inertia force acting on the soil layer, N;
- \( F_d \) – force to counteract soil deformation, N;
- \( G \) is the weight of the soil layer (gravity), N;
- \( N \) is the force of action of the working body on the soil layer, N;
- \( F_{fr} \) – friction force, N.

Soil deformation resistance of the soil \( F_d \) is the vector sum:

\[
\vec{F}_d = \vec{F}_{fr} + \vec{F}_{Fd} + \vec{F}_{fg}
\]

where \( F_{fr} \) – resistance to soil chipping, H;
- \( F_{Fd} \) – soil anti-shear strength, H;
- \( F_{fg} \) – soil anti-compression force, H.

![Figure 3. Scheme of forces acting on the working body.](image)

We obtain an expression for determining the weight of the soil moved by the working body, going to the formation of the ridge, per unit time (mass flow) taking into account the physical properties of the soil and the analytical expressions of the forces acting on the working body:

\[
M_r = \xi \left( k \cdot \frac{r^2}{\sin 2\varphi} \cdot \frac{\pi}{180} (\sigma - \sin \sigma) \cdot \cos \beta + f \cdot \left( c \cdot \sin \alpha + \frac{a^2}{a-c} \cdot \sin \alpha \right) \cdot b \cdot \cos \beta \cdot v_c \cdot \gamma_v - \xi \cdot 0,05 \cdot \rho \cdot S_S \cdot \sqrt{\frac{r \cdot g \cdot \cos \psi \cdot \cos \varphi - L(f \sin \psi + 1)}{1-2^r}} \right)
\]

(2)

where:
- \( k \) – soil losses that occur when the cultivating part of the working body moves from the central part of the aisle to the periphery;
- \( \xi \) – soil loss for shedding and scatter, taken equal 0,6;
- \( f \) – coefficient of friction;
- \( \gamma_v \) – bulk soil weight, g/cm³;
- \( \beta \) – paw opening angle, deg.
- \( S_S \) – cross-sectional area of the soil carried by the dump, m²;
- \( \rho \) – soil density, kg/m³.

The physical meaning of the indicator of the mass flow rate of soil \( M_r \), moved by the working body, for the formation of the ridge in accordance with agrotechnical requirements is that it shows the weight of the soil, which is moved by the working body to form the ridge at a speed of \( v_c \) for a time \( t \) equal to one second. Let us move from mass flow to specific volume:

\[
V_r = \frac{M_r}{v_c \rho}
\]

(3)
The obtained dependences 2 and 3 allow us to determine the ranges of technological and geometric parameters of the working body, at which a ridge is formed with the parameters in accordance with agricultural requirements.

3. Results and discussion

Based on the mathematical model, we will construct the response surfaces (figure 4–6):

**Figure 4.** Response surface: $V_r = f(\alpha, v_c)$, $r = 0.3$ m; $\Psi = 10^\circ$; $\varphi = 66^\circ$; $h = 0.09$ m; $L = 0.15$ m.

**Figure 5.** Response surface: $V_r = f(\varphi, \Psi)$, $\alpha = 0.6$ m; $r = 0.3$ m; $v_c = 3$ m/c; $h = 0.09$ m; $L = 0.15$ m.

**Figure 6.** Response surface: $V_r = f(h, r)$, $\alpha = 0.6$ m; $\Psi = 10^\circ$; $\varphi = 66^\circ$; $v_c = 3$ m/c; $L = 0.15$ m.
We find rational ranges of the values of the working body parameters from the obtained dependencies and the response surfaces constructed from them:

Technological:
– soil cultivation depth: $a$ – has the greatest influence on the volume of ridge formation, the rational range of the parameter is within 4–10 cm.

Construction:
– the screw radius $r$, the rational range of the parameter is within 0.2–0.3 m;
– the width of the cross section of the blade $h$ has a directly proportional effect on the volume of the moved soil and providing its optimal value at values $h = 0.07$–0.09 m;
– the screw elevation angle $\phi$, has rational values in the range $60^\circ$–$70^\circ$;

The remaining parameters, such as: MTA speed $v_s$, elevation angle of the screw axis $\Psi$ and the length of the blade generatrix $L$ do not significantly affect the ridge formation.

4. Conclusion
Analytical dependences are obtained, which make it possible to determine the influence of structural and technological parameters on the formation of the ridge during the processing of row-spacing by the working body of the cultivator-dump type. This made it possible to choose rational ranges of their values: screw radius $r$ in the range 0.2–0.3 m, blade width $h$ of 0.07–0.09 m, screw elevation angle $\phi$ of $60^\circ$–$70^\circ$.

The studies conducted in the field experiment in the soil channel and directly in the field established the rational shape and size of the working body of the cultivator-dump type. The ridge volume $V_{gr}$ corresponding to the agrotechnical requirements was achieved with a soil cultivation depth $a$ of 6 cm, a screw radius $r$ of 0.3 m, a blade cross section $h$ of 0.08 m and a screw angle of elevation $\phi$ of $60^\circ$.

The created mathematical model of the interaction of the working body with the soil and modeling of the process of crest formation will allow the creation of new tools for inter-row cultivation of row crops.

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