KAPITEL 2 / *CHAPTER 2* [2]
STUDY OF PARAMETERS OF WORKING BODIES OF CONTINUOUS ACTION OF INCREASED PRODUCTIVITY

DOI: 10.30890/2709-2313.2024-32-00-001

Introduction

Earth-moving equipment in highly developed countries takes a leading place among all self-propelled and trailed equipment of various purposes, from underwater to space.

Such technology is based on the scientific and technical principles of creating high-speed, low-energy technologies and mobile technology for the destruction of natural and artificial environments (soils, rocks, silt, reinforced concrete, bricks, etc.) in various conditions (ground - road, agricultural land cultivation, engineering and military and emergency rescue work, cleaning of soil from pollution, reclamation, irrigation, creation of trenches, canals, trenches, storages, etc.; underground - extraction of minerals, construction of tunnels, subways, creation of storage of contaminated and radioactive soil and materials, laying of oil, gas, water, and communication lines; underwater - cleaning the bottom of rivers, reservoirs, seas from pollution, underwater construction, laying of underwater pipelines, river crossings and communication lines; space - creation of automated tools for soil development and containerization and rocks of space objects).

One of the ways of intensifying the development of strong soils is the use of continuous machines, which most often use disk working bodies.

2.1. Earthmoving equipment of increased productivity

Most machines for earthworks destroy the mass of soil by successive separation of chips. The movement of cut rock along the working body, as well as the accumulation of rock in front of it, in some cases cause significant resistance forces on

[2]***Authors:*** *Gorbatyuk Ievgenii Volodymyrovych*

 ISBN 978-3-98924-060-5

the working body (as a rule, higher than, respectively, from destruction).

Digging is the process of separating the rock from the massif, which includes cutting the soil, moving it along the working body and in front of the latter, and in some cases, moving it inside the working body (in the buckets of scrapers, excavators) and rubbing the working body against the rock.

Cutting is the process of separating the rock from the massif using the cutting part of the working body, which usually has the shape of a wedge. The cutting part of the working body is characterized by the sharpening angle, the rear angle, the front angle, the cutting angle, and the width of the cutting edge.

In most earthmoving machines, the working body moves most often in two directions. One of them is the pressure at which the chip separates; the other is a feeding movement, during which the thickness of the chip changes. The feed speed is usually several times lower than the speed of the main movement.

Introduction into the rock occurs as a result of simultaneous movement of the knife in depth and forward. In some cases, the knife first moves deep into the soil, and then moves forward to separate the chips, in others, these two movements are carried out during the entire cutting process or most of it (buckets of excavators, tools of drilling machines). Efforts and rational modes of the cutting and digging process are selected on the basis of experimental research [1-3].

During the operation of the disc working bodies, the processes of soil destruction and its removal occur at the same time, then the process of interaction of the disc working body with the soil can be considered as a process of soil digging.

A promising direction in the development of working bodies of continuous earthmoving machines is the development and construction of working bodies with the possibility of regulating the flow of soil removal.

In such working bodies, the removal of soil from the hole is done under the action of centrifugal forces. The soil goes to the periphery of the working body and is held by the walls of the hole. When reaching the day surface of the hole, the soil is thrown. During transportation, the soil is divided into two streams. The soil, which falls on the flat part of the transport elements under the action of centrifugal forces, is carried out of the hole. However, the soil, which has low kinetic energy (hence low speed), does not have time to travel all the way from the center of the working body to the periphery, in addition, the working body also has translational movement, falls into the conical or pyramidal part of the soil-bearing elements, where it receives additional the energy charge (because it continues to make a rotational movement with the working body and receives additional energy with each rotation) and moves along the generator to the peripheral part of the working body and is transported with the punch through the open bases of the cone or pyramid. Due to the fact that the working body is made together with the soil-bearing elements, during transportation, there is no change in the direction of the transport speed vector of soil particles, which also leads to a decrease in energy costs for soil transportation.

In this technical solution, oriented soil flows are created, thereby reducing energy costs for unproductive mixing of the soil developed by the working body during its transportation.

In the course of the analysis of the existing constructions of the working bodies of continuous action earthmoving machines, it was concluded that one of the main disadvantages of the existing working bodies of continuous action machines is the high energy consumption of the development of the soil mass due to the mixing of the soil in the zone of interaction of the knife with the soil mass, which leads to difficult removal of soil from the face and unproductive expenses for soil mixing, their great complexity and metal content with a rather low specific productivity.

2.2. Kinematic parameters of the working body of continuous action of increased productivity

To determine the rational design of the working body, and especially soil-bearing elements, it is necessary to determine the kinematic parameters of the working body. To calculate the carrying capacity of the soil-bearing elements of the working body, it is also necessary to determine the volume of shavings that are cut in one revolution of the working body. It is necessary to develop a mathematical apparatus for determining the kinematic parameters of the movement of soil particles along soil-bearing elements of different configurations. The most effective soil-bearing elements, in our opinion, will be soil-bearing elements that are made in the form of a part of a cone, since this shape will contribute to the least sticking of the soil. It is best that the soil-bearing elements are made in the form of a part of an elliptical cone. The main advantage of such soil-bearing elements will be a reduced soil transportation path because the length of the arc of half an ellipse is shorter than the length of the arc of half a circle, which will significantly reduce the energy costs of friction during soil transportation [4].

When developing the mathematical apparatus, the following basic assumptions and limitations were taken:

• when acting on the soil, the cutting element does not affect the force of cutting the soil by the cutting element that is located nearby;

• a number of cutting elements, located at the same distance R_i from the axis of rotation of the disk, work according to the scheme "track in track";

• there is an infinitely large number of identical soil-bearing elements on the disc, and the thickness of these soil-bearing elements is zero. This assumption means that each elementary soil particle is directed along its soil-bearing element;

• the forces of interaction between soil particles are not taken into account.

Let's determine the trajectory of the soil particle along the soil-bearing elements, which broke away from the main massif. The motion of the particle will be complex. It will consist of the movement of the particle from the center of the working body under the action of centrifugal forces and rotational and translational movement with the working body.

Let's imagine the working process of the movement of a soil particle along the soil-bearing elements of the working body made in the form of a cone in Cartesian coordinates (Figure 1).

The equations of motion of a soil particle along soil-bearing elements will be as follows:

 ISBN 978-3-98924-060-5

$$Y = R_i \cos\varphi;$$
$$Z = R_i \sin\varphi + V_m t;$$
$$X = V_x t, \qquad (1)$$

where V_m – speed of feeding the working element to the face; V_x – speed of movement of the soil flow along the x-axis; R_i – distance to the z-axis of the and i-th soil particle; φ – angle of rotation of the working element.

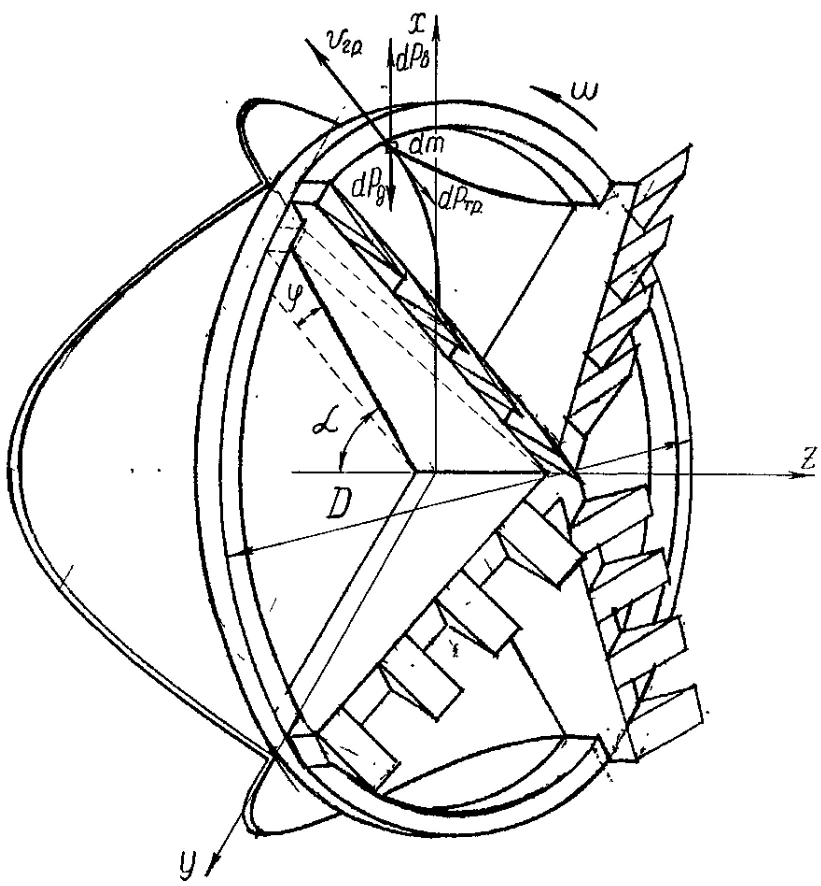

Figure 1 - Scheme for determining the kinematic parameters of the movement of a soil particle along the soil-bearing elements of the working body

Given that $\varphi = \omega t$, convert the system (1) to the form:

$$Y = R_i \cos\omega t;$$
$$Z = R_i \sin\omega t + V_m t;$$
$$X = V_x t. \qquad (2)$$

where ω – angular speed of working organ.

To find the kinematic parameters, we differentiate each equation of the system (2), determine the projections of the velocities of soil particles moving along the soil-bearing elements:

$$\begin{aligned} V_y &= dy/dt = -R_i \omega \sin \omega t; \\ V_z &= dz/dt = R_i \omega \cos \omega t + V_m; \\ V_x &= dx/dt = V_x. \end{aligned} \tag{3}$$

Separating the variables we get in differentials:

$$\begin{aligned} dy &= -R_i \omega \sin \omega t dt; \\ dz &= (R_i \omega \cos \omega t + V_m) dt; \\ dx &= V_x dt. \end{aligned} \tag{4}$$

From the system of equations (4) according to the known formula of the arc differential [4] we find the way of transporting the soil particle along the soil-bearing elements:

$$ds = \sqrt{(dx)^2 + (dy)^2 + (dz)^2}$$

or

$$ds = (\sqrt{R_i^2 \omega^2 \sin^2 \omega t + R_i^2 \omega^2 \cos^2 \omega t + V_m^2 + 2R_i \omega V_m \cos \omega t + V_x^2}) dt.$$

After the transformations, we get:

$$ds = (\sqrt{R_i^2 \omega^2 + V_m^2 + V_x^2 + 2R_i \omega V_m \cos \omega t}) dt. \tag{5}$$

Let's integrate equation (5):

$$\int ds = \int \sqrt{R_i^2 \omega^2 + V_m^2 + V_x^2 + 2R_i \omega V_m \cos \omega t} dt. \tag{6}$$

To solve the right side of the expression (2.6), we introduce a replacement

$$\begin{aligned} R_i^2 \omega^2 + V_m^2 + V_x^2 &= A; \\ 2R_i \omega V_m &= I. \end{aligned}$$

Then

$$\int ds = \int \sqrt{A + I \cos \omega t} dt.$$

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From here

$$s = \frac{\sqrt{I}}{\omega} \int \sqrt{A/I + \cos\omega t}\,dt,$$

and the solution will look

$$s = -\frac{2\sqrt{A+I}}{\omega} E(\psi, r) + c, \tag{7}$$

where s – way of transporting the soil along the soil-bearing elements, $E(\psi, r)$ – elliptical integral of the second kind,

$$\psi = \arccos\sqrt{(1-\sin\omega t)/2}; \quad r = \sqrt{2I/(A+I)},$$

where c – integration constant, which is determined by the boundary conditions:

$$t = 0; \;\; s = 0; \;\; c = (2\sqrt{A+I}/\omega); \;\; [E(\pi/4, r)].$$

Finally we find:

$$s = 2\sqrt{A+I}/\omega; \;\; [E(\pi/4, r) - E(\psi, r)]. \tag{8}$$

Rate of interaction of soil-carrying elements with soil:

$$V = \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2}, \tag{9}$$

or

$$V = \sqrt{R_i^2\omega^2 + V_m^2 + V_x^2 + 2R_i\omega V_m \cos\omega t} \tag{10}$$

We find the relationship between the distance from the axis of the working body to the soil particle and determine the geometric parameters of the soil-bearing elements of the working body.

The soil-carrying elements of the working element, for example, are made in the form of an elliptical cone, the equation of which has the form:

$$X^2 = K^2(Y^2 + Z^2), \tag{11}$$

where K – a coefficient that depends on the geometric properties of the cone.

$$K = \mathrm{tg}\alpha,$$

where α – angle of inclination of the twist cone to the ZOY plane.

Substituting the system of equations (1) into the cone equation (11), we get:

$$V_x^2 t^2 = (R_i^2 \cos^2 \omega t + R_i^2 \sin^2 \omega t + V_m^2 t^2 + 2R_i V_m t \sin \omega t) K^2$$

or

$$V_x^2 t^2 = (R_i^2 + V_m^2 t^2 + 2R_i V_m t \sin \omega t) K^2 .$$

After the transformations, we get:

$$R_i^2 + 2R_i V_m t \sin \omega t + V_m^2 t^2 - \frac{V_x^2 t^2}{K^2} = 0 .$$

From here

$$R_i = (\frac{\sqrt{V_x^2 - V_m^2 K^2 \cos^2 \omega t} - V_m K \sin \omega t}{K}) t. \quad (12)$$

Soil flow velocity along x axis:

$$V_x = \frac{1 - \sin \mu}{\cos \mu} K_a R_i \omega,$$

where K_a – approximating coefficient, which takes into account the effect of the Coriolis force on the flow of soil moving along the soil-carrying elements, μ – friction angle of the moving soil along the material of the soil-carrying elements.

Substituting the value V_x into the expression (12) and making the transformation we get:

$$R_i = \frac{V_m t \left(\sqrt{\sin^2 \omega t + \frac{\omega^2 t^2 K_a^2 \cos \mu}{K^2} - 1} - \sin \omega t \right)}{1 - \frac{\omega^2 t^2 K_a^2 \cos \mu}{K^2}}$$

or

$$R_i = \frac{K V_m t \left(\sqrt{\omega^2 t^2 K_a^2 \cos \mu - K^2 \cos^2 \omega t} - K \sin \omega t \right)}{K^2 - \omega^2 t^2 K_a^2 \cos \mu} . \quad (13)$$

As a result of the transformations, the equations of the movement of soil flow

 ISBN 978-3-98924-060-5

along the elliptical cone of soil-carrying elements and the speed of flow along the x-axis are obtained (Figure 2), which makes it possible to design working bodies with given parameters of soil-carrying elements minimizing the path of the flow of soil along them.

We will conduct a study of the speed function. To do this, we differentiate equation (10):

$$V' = -\frac{R_i \omega^2 V_m \sin \omega t}{\sqrt{R_i^2 \omega^2 + V_m^2 + V_x^2 + 2 R_i \omega V_m \cos \omega t}}. \quad (14)$$

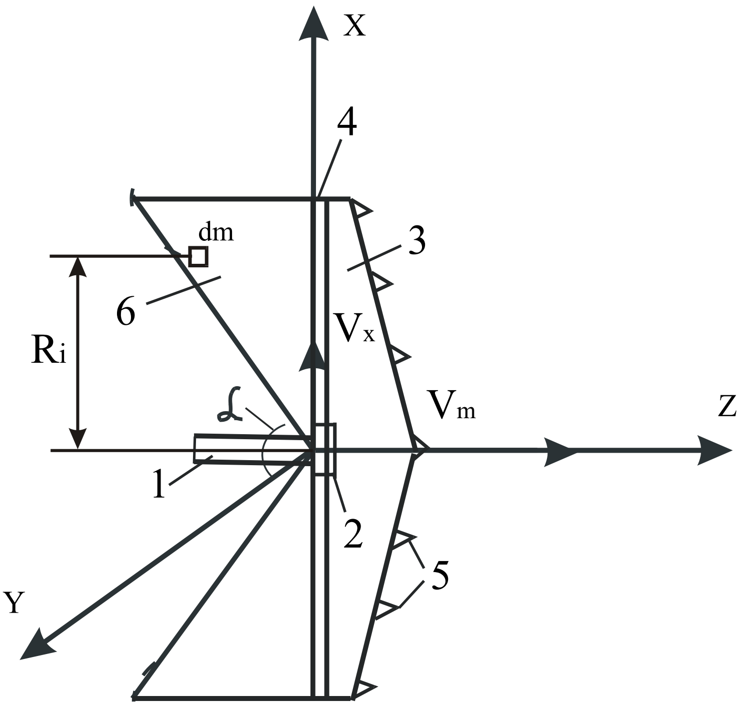

Figure 2 - Diagram of excavator working body:

1 – drive shaft; 2 – hub; 3 – transportation elements; 4 – rim; 5 – cutting elements; 6 – soil-carrying elements; dm – elementary soil particle

Since the acceleration we received with a minus sign, this means that the increase in speed during the movement of soil particles to the periphery of the working body decreases, that is, the acceleration of the soil particle decreases.

To find the maximum of the function, the derivative must be equated to zero.

Equating equation (14) to zero, we will see that the acceleration of the soil particle will be maximum at the moment of its separation from the soil mass.

To determine the speed of interaction of the cutting elements with the soil and the thickness of the chips cut by one element Δh, we use the formula of the length of the line (arc) of contact with the soil S_P for any point of the cutting edge [5, 6]:

$$S_{\text{P}} = \frac{\alpha_k s}{2\pi}, \tag{15}$$

where $\alpha_k / 2\pi$ – coefficient characterizing the degree of efficiency of use of the working surface of the body; α_k – angle of contact of the cutting elements with the ground, equal to

$$\alpha_k = \pi + 2\arcsin\frac{H - R_i}{R_i}, \tag{16}$$

where H – depth of the detached trench.

The rate of interaction of the soil-destroying element with the soil at any point of the arc is determined from the expression (9):

$$V = \sqrt{V_m^2 + R_i^2\omega^2 + R_i^2\omega^2\cos^2\omega t + 2V_m R_i\omega\cdot\cos\omega t}. \tag{17}$$

The thickness of the soil chips cut by one cutting element is taken equal to the kinematic depth of the tooth cutting, which is fixed on the working body, that is, the distance in the feed plane between the previous trajectory of the soil-destroying element and the current one, set normal to the latter. For each soil-breaking element, the kinetic depth of cutting is a variable, varying from a certain value to a maximum. It depends on the speed of movement of the base machine, the circular speed of the element, the number of cutting elements m operating "footprint to footprint," the angle of contact with the ground and can be defined [7] as

$$\Delta h = \frac{\phi C\sin\varsigma}{2\pi}, \tag{18}$$

where ϕ – angle between adjacent soil-breaking elements operating "track to track", C – feed of the element in the plane of movement of the base machine for one turn of the working element, ς – angle between the vectors of cutting and feed speeds.

Given that

$$C = \frac{2\pi V_m}{\omega}, \tag{19}$$

$$\varsigma = \arccos\left[\frac{R_i\omega \cdot \cos\omega t + V_m}{\sqrt{V_m^2 + R_i^2\omega^2 + R_i^2\omega^2\cos^2\omega t + 2V_m R_i\omega \cdot \cos\omega t}}\right] \tag{20}$$

and substituting expressions (17; 19 and 20) in the ratio (18), we get:

$$\Delta h = \left(\phi V_m R_i\right)/V_i\,. \tag{21}$$

Note that the expression (21) with sufficient accuracy can be used with small values ϕ of justification, when the arc length of the cutting path, which is tightened by an ϕ angle, is approximately taken equal to the chord. Otherwise, this expression will give some calculation error.

To find the thickness of the chips, go to the cylindrical coordinates, then the trajectory of the *i*-th cutting element can be described by a system of equations:

$$\begin{aligned} X &= \rho\cos\varphi; \\ Y &= \rho\sin\varphi; \\ Z &= Z, \end{aligned} \tag{22}$$

where $\varphi = \omega \cdot t$ – angle of rotation of the working organ; $\rho = \sqrt{X^2 + Y^2 + Z^2}$ – radius vector at the point with coordinates (X, Y, Z).

Squaring the equations and adding them, after the transformations, we get

$$\rho^2 = \left(R_i^2 + 2b_i^2\right) + \left(\frac{V_m\varphi}{\omega}\right)^2 + \left(\frac{2V_m b_i\varphi}{\omega}\right) + \left(\frac{2V_m R_i\varphi \cdot \sin\varphi}{\omega}\right) + R_i^2\sin^2\varphi \tag{23}$$

or

ISBN 978-3-98924-060-5

$$\rho = \sqrt{(R_i^2 + 2b_i^2) + \left(\frac{V_m\varphi}{\omega}\right)^2 + \left(\frac{2V_m b_i\varphi}{\omega}\right) + \left(\frac{2V_m R_i\varphi \cdot \sin\varphi}{\omega}\right) + R_i^2 \sin^2\varphi}\,, \tag{24}$$

where b_i – height of the *i*-th cutting element from the plane of the working element along the *z* axis.

Given that

$$M = R_i^2 + 2b_i^2;$$
$$D = \left(\frac{V_m}{\omega}\right)^2;$$
$$E = \frac{2V_m b_i}{\omega};$$
$$K = \frac{2V_m R_i}{\omega};$$
$$L = R_i^2, \tag{25}$$

transform the expression (24) using equation (25)

$$\rho = \sqrt{M + E\varphi + D\varphi^2 + K\varphi\sin\varphi + L\sin^2\varphi}. \tag{26}$$

The equation of the normal to the trajectory curve at this point can be written in the form of an ordinary first-order differential equation $F(\varphi,\rho,\rho')=0$

$$-d\rho_j / d\varphi_j (\rho_{j+1} - \rho_j) = \varphi_{j+1} - \varphi_j, \tag{27}$$

where ρ_j, ρ_{j+1}, φ_j, φ_{j+1} – are current values of radius vectors and rotation angles.

$$\frac{d\rho_j}{d\varphi_j} = \frac{1}{2} \cdot \frac{2D\varphi_j + E + K\varphi_j\cos\varphi_j + K\sin\varphi_j + 2L\sin\varphi_j\cos\varphi_j}{\sqrt{M + E\varphi_j + D\varphi_j^2 + K\varphi_j\sin\varphi_j + L\sin^2\varphi_j}}. \tag{28}$$

Given that the shortest distance between two points is:

$$\sqrt{(X_{j+1} - X_j)^2 + (Y_{j+1} - Y_j)^2 + (Z_{j+1} - Z_j)^2}, \tag{29}$$

chip thickness can be defined as the difference in absolute values of radius vectors, i.e.

$$\Delta h = \left|\rho_{j+1} - \rho_j\right| = \left|-\frac{\varphi_{j+1} - \varphi_j}{d\rho_j / d\varphi_j}\right|. \tag{30}$$

Conclusions

The considered dependencies (18, 21, 30) allow us to determine the volume of chips cut in one revolution of the working body, that is, we can calculate the throughput of soil-carrying elements of the working body. With the specified technological parameters (bottomhole dimensions, etc.), it is possible to calculate not only kinematic (speeds of interaction of soil-carrying and soil-destroying elements with the soil, distances from the axis of the working body to the soil particle), but also geometric indicators (angle of inclination of the vertical cone) necessary for the design of working bodies with oriented flows of soil removal.

 ISBN 978-3-98924-060-5