ANALYSIS OF STRUCTURES AND THE PROCESS OF CUTTING SOIL WITH AN INERTIAL ROTOR

Abstract. Increasing the flow rates of the main work processes is one of the promising ways to achieve the highest productivity of earthmoving machines. In this regard, the requirements of increasing the maneuverability and mobility of these machines while simultaneously increasing output, reducing their weight, and specific energy consumption of work processes leads to the widespread use of continuous transport with rotary machines of layered development. One of these new types of machines are excavating and transport machines with an inertial rotor of lower unloading, which can be widely used when performing large volumes of excavation, stripping and mining operations in the mining, reclamation and construction industries. The paper presents the results of studies of high-speed digging and suggests a method for determining the average energy intensity of soil transportation, and the proposed equations can be recommended for calculating the inertial rotor. The table of costs of specific energy intensity and productivity from the speed of rotation of the rotor at constant chip sizes is given.

Keywords. Inertial rotor of lower unloading, Bucket rotor, Bucket-free rotor, Cutting knives, Specific energy intensity of digging.

Introduction
The prospect of creating and developing excavating and transport machines covers a wide range of issues due to the diversity of their technological purpose and design. The well-known advantages of such machines contribute to the spread of rotary transport machines: significantly higher productivity and lower energy consumption compared to single-bucket excavators, the possibility of using in-line technology of work. The advantages of such machines should also include the possibility of selective excavation and obtaining the required lumpiness. Rotary transport machines are now widely used in the production of earthworks in construction conditions, loading and unloading operations, etc.
The energy consumption of the digging process in most studies is considered as a whole, without separation into constituent elements, which does not allow to identify the degree of influence of individual factors on the digging process (Figure 1). The available methods of separate determination of the energy consumption of the digging process are mostly limited, insufficiently accurate and have not been widely used. With high-speed digging, there are additional influencing factors that further complicate the study of the digging process [1].

One of the ways to increase the efficiency of the excavation process should be the use of bucket-less inertial rotors. The proposed bucket-free inertial rotor, which develops the face with the front cutting part of the knives and transports the cut soil in a continuous flow, is the most promising today.

Comparative studies of three types of cutting elements - a bucket without a bottom, an arched perimeter and a knife - under the same conditions showed the advantages of a knife-type cutting element (Figure 2, a). In the speed range from 2 to 9 m/sec, the knife cutting element has not only the lowest specific energy intensity, but also a lower degree of its increase with increasing speed [1].

Figure 1 - Process of inertial rotor operation

![Figure 1 - Process of inertial rotor operation](image_url)
Figure 2 - Schemes of inertial rotors:

- a - bucketless; b - bucket; \( B_H \) - width of pairs of knives; \( L_H \) - length of pairs of knives; 
- \( B_K \) - width of buckets; \( L_K \) - bucket length; \( D_p \) - rotor diameter; \( \nu_n \) - conveyor speed; \( \beta \) - soil excavation angle; \( \beta_p \) - angle of beginning of cutting by the rotor; \( c(\beta) \) - regularity of soil distribution during transportation between knives; \( c(\pi) \) - regularity of soil distribution by angle \( \pi \)

The results of these studies confirmed the prospects and expediency of continuing studies of the inertial rotor at high speeds.

In this paper, the results of further studies of high-speed digging are presented and a method for determining the specific energy intensity of the digging process by an inertial rotor, taking into account the speed, is proposed.

Experiments were carried out in the speed range from 2 to 9 m/sec, allowing to separate the processes of digging and cutting the soil with an inertial rotor. When working with two rows of knives, the soil was separated from the array, transported in a continuous stream along the face and completely unloaded along the rotor. When experimenting with one row of knives, the cutting process was carried out - only the chips were separated without transportation, the cut soil collapsed to the bottom of the face.

Taking into account the influence of speed, the digging power of the inertial rotor can be written as:

\[
N_k = k_y N_p + N_T, \quad (1)
\]

where

- \( N_k \) - the power of digging the soil to the rotors;
- \( N_p \) - is the part of the digging power spent on cutting the soil at a cutting speed close to zero (determined experimentally when the rotor is operating with one row of knives);
- \( k_y \) is the experimental coefficient of the influence of the cutting speed, taking into account the increase in the resistance of the ground to cutting with increasing speed;
- \( N_T \) - is the part of the power spent on transportation of cut soil.

The accumulated experience of working at the stage of scientific research and the use of a bucket-less inertial rotor of the lower unloading showed a number of highly effective advantages...
of its design and workflow, which made it possible to identify the perspectivity of its application. Theoretical and experimental studies of prototypes of machines with an inertial rotor in field and production conditions, as well as a comparative technical and economic analysis of their parameters with existing rotary machines gives every reason to assert the need for their early introduction into production.

The fundamental difference of the new rotor is that it also moves along the torus like all the rotors of boom excavators, but developing the face not with buckets and from the bottom up, but with descending cutting knives in two or three rows from top to bottom with the transportation of cut soil along the face, the receiving tray and subsequent unloading it onto the conveyor located behind it in the course of its rotation, i.e., oblique cutting of the face with knives is practically carried out with the collapse and ejection of the cut material under the action of its mass and centrifugal forces onto the conveyor at an initial speed.

Thus, the use of a continuous excavator-transport machine with a bucket-less inertial rotor in road construction provides the following advantages [2]:

1) a sharp increase in productivity due to the possibility of using increased digging speeds and high transport capacity of the inertial rotor (increased height of the cutting and transport elements of the rotor);
2) reduction of the specific energy intensity of digging, due to the use of oblique cutting with the collapse of the excavated material and the possibility of investing the mass of the inertial rotor, working equipment or the entire machine (with rigid suspension of working equipment) in the digging process;
3) reduction of specific transport energy consumption of continuous operation, or the material is fed to these means at an initial speed.

Materials and Methods.

In order to determine the energy intensity of soil transportation, the performance of the inertial lower unloading rotor in various soils and to establish rational modes of its operation, the authors carried out experimental work in the field. Studies were carried out in sandy and clay soils of categories II-III. Soil density was measured with a DorNII striker at three levels along the height of the developed layer. On average, it was 12-16 strokes in the upper and 16-26 strokes in the lower layers. The cutting elements were attached to the rotor so that it was possible to change the number of pairs of knives (4, 8 and 10), the distance between them (275, 310 and 345 mm) and the angle of their installation relative to the edge of the rotor drum (6-16 degrees) [3].

To determine the energy consumption for transporting the soil by the inertial rotor of the lower unloading MT at various speeds, it can be assumed that the soil in the process of transportation is evenly distributed between the knives along the width, and along the knives - according to some regularity c (β). To determine this pattern, we believe that the number of knives is infinitely large, so the width of the chips removed by one knife tends to zero. Then the chip volume V can be written (Figure 3, a) [4]:

\[
V_c = \frac{\beta}{2} a_o \sin \beta b_o R_p d\beta = R_p - b_o \cdot a_o \cdot (\cos \beta' - \cos \beta) \tag{2}
\]
Then the total volume of soil moving along the cutting surface will be:

\[
V = \sum_{i} V_{i} = a_{o} \cdot b_{o} \cdot R_{p} \left[ n_{z} \cos \beta' - \sum n_{i} \cos \left( \beta' - i\beta \right) \right],
\]

where \( a_{o} \) and \( b_{o} \) - respectively height and width of chips;
\( R_{p} \) - rotor radius;
\( n_{z} \) - number of cutting knives;
\( \beta_{z} = \frac{2\pi}{z} \) - angle corresponding to arc of ladle trajectory between cutting edges of adjacent knives.

The total volume of removed chips is measured cyclically, and during cycle time corresponding to time of rotation of rotor by angle increases according to linear law. This volume for the experimental rotor of diameter \( D_{p} = 1,54 \text{ m} \) and 10 pairs of knives at \( a_{o} = 200\text{mm}, b_{o} = 31\text{mm} \), varies from 0,125 to 0,195 \( \text{m}^3 \) and averages 0,16 \( \text{m}^3 \).

For determination of energy intensity for soil transportation by inertial rotor it can be assumed that number of knives is unlimited large, therefore width of removed chips tends to zero \([4]\). To determine this pattern, consider an elementary ladle whose position in the bottom hole is determined by the angle \( \beta \), then the elementary volume of chips cut by the ladle is equal (Figure...
3, b):

\[ dV = v_n dt \int_{\beta}^{\beta'} a(\beta) \cdot R_p d\beta. \]  \hspace{1cm} (4)

The elementary volume of soil in the bucket can be written as

\[ dV = BR_p c(\beta) d\beta. \]  \hspace{1cm} (5)

where \( v_n \) - rotor feed speed;
\( B \) - ladle width (distance between paired knives);
\( R_p \) - rotor radius.

By matching (4) and (5), an expression can be obtained for \( c(\beta) \) (Figure 3, d);

\[ c(\beta) = \frac{v_n}{B \omega} \int_{\beta}^{\beta'} a(\beta) d\beta, \]  \hspace{1cm} (6)

where \( \omega \) - rotor angular velocity.

The average value of the torque on the rotor shaft developed during the transportation of soil over the cutting surface can be found by applying the theorem on changing the kinetic moment of a point of variable mass, according to which the time derivative of the kinetic moment of a point of variable mass is equal to:

\[ M_z = \frac{dL_z}{dt}, \]  \hspace{1cm} (7)

Value is composed of moment \( M_B \) of forces of particles weight, moment \( M_T \) of friction forces of cut soil against cutting plane, moment of reactions acting on bucket walls equal to value of torque \( M_k \).

In accordance with this, the torque on the rotor shaft

\[ M_k = M_B + M_T + \frac{dL_z}{dt}. \]  \hspace{1cm} (8)

To determine \( \frac{dL_z}{dt} \) - we assume that the velocity vector \( v = const \), because the absolute velocity of the particles removed at the time of the cut is zero, then when calculating the increment \( dL_z \), we take into account the kinetic moment at the exit from the face [6].

The second number of attached soil masses in the buckets is determined, bearing in mind that the buckets (knives), which are simultaneously in the process of cutting, cut off chips with a width of:

\[ M_k = M_B + M_T + \frac{dL_z}{dt}, \]  \hspace{1cm} (9)

And the flow rate per time \( dt \) will be equal \( V_c dt \), therefore, taking into account (9), we
can write:

\[
\frac{dL_z}{dt} = c(\pi) \omega^2 B \gamma \left[ R_p - \frac{c(\pi)}{2} \right]^2.
\]

(10)

where \( \gamma \) - volumetric weight of soil;

\( g \) - acceleration of gravity.

The moment of the forces of weight and friction can be respectively expressed by the formulas:

\[
M_B = -\gamma B \frac{\beta}{\pi} c(\beta) \left( R_p - \frac{c(\beta)}{2} \right)^2 \sin \beta d\beta
+ \gamma(p)B \frac{c(\beta)}{R_p} \left( R_p - \frac{c(\pi)}{2} \right)^2 \left( 1 - \cos \beta_p \right)
\]

(11)

\[
M_T = \int_{\beta}^{\pi} \gamma R_p \sin \beta \left( R_p - \frac{c(\beta)}{2} \right)^2 c(\beta)B \omega^2 R_p f_T \cos \beta d\beta
+ \gamma\left( R_p - \frac{c(\pi)}{2} \right)^2 c(\pi)Bf_T R_p \omega^2 \beta_p.
\]

(12)

**Results and Discussion**

Simplifying these equations and substituting their values into formula (6), it can be obtained that the energy intensity of soil transportation is 28% for an experimental inertial rotor, in this regard, the obtained equations can be recommended for calculating the proposed inertial rotor.

**Figure 4** - Dependence of specific energy intensity and capacity costs on rotor rotation speed at constant chip sizes (\( H = 1150 \text{ mm}, a_0 = 200 \text{ mm}, b = 31 \text{ mm} \)): 1 - curve of change of specific energy intensity; 2 - performance curve.

Analysis of the results of Table 1 (Figure 4) shows that the energy intensity of soil transportation increases with increasing rotor speed, while the performance of the inertial rotor grows linearly.

The development of the face was carried out with vertical chips "from top to bottom"; when
working with two rows of knives (16 pieces), the soil was transported along the face and unloaded along the rotor; when cutting with one row of knives (8 pieces), the cut soil collapsed to the bottom of the face.

Calculations show that the size of the soil discharge zone on the belt depends on the transport loading of the rotor and exceeds the size of the soil section at the time of separation by no more than 1.4 - 1.8 times, and the speed practically does not change.

**Table 1** - Costs of specific energy consumption of soil transportation and productivity of the inertial rotor depending on the rotor speed at constant chip sizes (H = 1150 mm, \( a_0 = 200 \) mm, \( b = 31 \) mm)

<table>
<thead>
<tr>
<th>Rotor speed ( \omega ), 1/sec</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy intensity, ( e ), kW*h/m³</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.05</td>
<td>0.07</td>
<td>0.09</td>
<td>0.11</td>
</tr>
<tr>
<td>Inertial rotor capacity P, m³/h</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>160</td>
<td>200</td>
<td>240</td>
<td>280</td>
<td>320</td>
<td>360</td>
<td>400</td>
</tr>
</tbody>
</table>

Experimental verification of the processes of soil unloading during the operation of rotors with a diameter of 1.54 m and 2.4 m at rotational speeds from 2 to 9 m/sec showed the acceptability of the calculated dependencies obtained.

The open zone of unloading the soil with an inertial rotor made it possible to make the necessary measurements of the unloading parameters - the unloading angle, the flight range of the soil particle and the size of the zone of the fall of the soil flow on the tape.

The results of the research have shown that the soil falls on the belt in a dense jet without loss of speed, which is very important for its further transportation by the receiving conveyor.

The analysis allows us to recommend the proposed excavating and transport equipment as a machine that performs a significant amount of work on excavation and movement of soil, as the most promising and cost-effective for the introduction of production and application in road construction.

**Conclusion.**

Summarizing the results of experimental studies, the following conclusions can be drawn:

1) a method for determining the average values of the energy intensity of soil transportation by an inertial rotor is proposed.

2) increasing productivity and reducing the weight of the machine can be carried out due to the possibility of developing an earthen mass with an inertial rotor of lower unloading at increased digging speeds and a large transport capacity of the working body;

3) reduction of specific energy consumption of work processes by 20-40%, which was recorded during field studies in soils of I-IV categories;

4) an increase in productivity by 6-10 times due to the ability to carry out the workflow at increased speeds and a high coefficient of height of the bucket (knives);

5) ensuring the possibility of developing soils and rocks with a humidity of 10-30% and a strength of up to 21N/cm² of non-explosive preparation.

All this contributes to the conclusion that the use of a new method of processing the face layer "on its own" in the excavator engineering makes it possible to create a number of excavator-loading equipment with a new rotor of high output, but small overall dimensions and weight, with reduced specific energy consumption for the working process of digging and transport, but with a
high specific cutting force.

In general, the research results have shown that the working equipment with the new inertial rotor of the lower discharge is quite operable, and also provides the development and transportation of soils of high humidity, and the material developed by knives is reliably transported by the rotor along the face and tray to the receiving conveyor, regardless of the height of the developed soil mass.

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REFERENCES


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