applied sciences

MDPI

Article

Determination of Continuous Earthmoving Machinery Course Stability under the Conditions of Cyclic Lateral Loading

Miroslaw Smieszek [1,*], Volodymyr Musiiko [2], Vasyl Mateichyk [1], Mykola Tsiuman [2], Andrii Koval [2] and Jakub Mościszewski [1]

[1] Department of Technical Systems Engineering, Rzeszow University of Technology, 8, Powstancow Warszawy Al., 35959 Rzeszow, Poland; vmate@prz.edu.pl (V.M.); j.mosciszews@prz.edu.pl (J.M.)

[2] Faculty of Automotive and Mechanical Engineering, National Transport University, 1, Mykhaila Omelianovycha, Pavlenka Str., 01010 Kyiv, Ukraine; musvd@i.ua (V.M.); tsuman@ukr.net (M.T.); kandr@i.ua (A.K.)

* Correspondence: msmieszk@prz.edu.pl

Abstract: This article presents the results of complex theoretical and experimental studies on creating universal continuous earthmoving machinery operating under non-standard loading conditions, namely, cyclic lateral loading on the actuator during digging. The lateral loading is due to the complex nature of the actuator motion when digging the soil, namely, the longitudinal motion of the machinery, the actuator digging the soil, and the lateral reciprocating motion of the actuator. This allows for variable width excavations in the soil, whose width exceeds the width of the actuator. The key issue of this machinery operation is to provide its course stability. The article considers the choice of soil-developing actuator and shows the developed calculation schemes of external loading on the operating equipment and a base tractor when digging long excavations in the soil. The dependencies to define external forces acting on the actuator when digging the soil and determining the machinery course stability, considering their spatial nature, have been developed and suggested for practical use. The conditions to ensure the stability of the course of universal earthmoving machinery have been formulated and substantiated. The developed method for determining course stability can be used when creating industrial samples of trenching earthmoving machinery.

Keywords: universal earthmoving machinery; operating equipment; lateral loading; soil; course stability; actuator

check for updates

Citation: Smieszek, M.; Musiiko, V.; Mateichyk, V.; Tsiuman, M.; Koval, A.; Mościszewski, J. Determination of Continuous Earthmoving Machinery Course Stability under the Conditions of Cyclic Lateral Loading. *Appl. Sci.* **2022**, *12*, 7029. https://doi.org/10.3390/app12147029

Academic Editor: Daniel Dias

Received: 20 May 2022
Accepted: 10 July 2022
Published: 12 July 2022

1. Introduction

The development of technology in the field of working machines and tracked vehicles made it possible to create new groups of machines intended for strictly defined earthworks. One of such groups is the machine that allows digging ditches. These machines are used in agriculture, drainage, pipeline laying and military applications. There is a tendency to universalize and reduce the size of these machines. As part of this trend, the aim is to create universal continuous earthmoving machinery (UEM) capable of developing excavations of different width and depth using the same actuator system [1–4]. These machines are used, in most cases, to work on the ground. The subject of the excavated material may be soil or rock [5]. However, solutions adapted to underwater works are appearing more and more often. Examples of such machines are described in other work [6,7]. One of the significant problems in the case of this type of tracked machine is ensuring the stability of motion under changing load conditions. This problem is described in many studies on the dynamics of this type of vehicle, in which models were created and experimental studies were carried out [8–12].

There are many patent solutions for creating universal machinery. A typical representative may be a trencher with a chain and bucket actuator [2]. It can perform lateral oscillating motions relative to the vertical hinge located aft of the tractor (Figure 1), thus changing the width of the excavation.

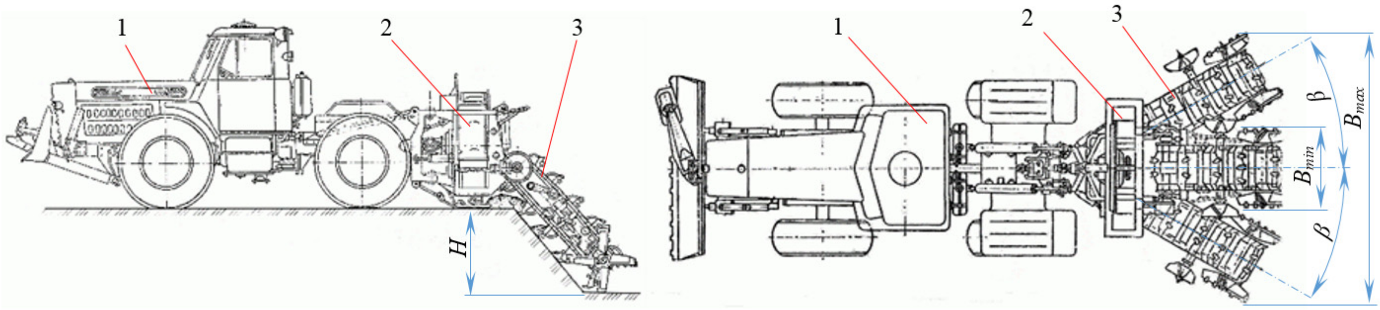

Figure 1. Machinery for digging trenches of variable width: 1—basic tractor; 2—rotary soil evacuator; 3—chain soil development actuator; H—digging depth; B_{min}—the minimum excavation width; B_{max}—the maximum excavation width; β—the angle of rotation of the actuator.

The amplitude of the actuator oscillating motion is determined by the value of the rotation angle of the operating equipment relative to the velocity vector of the longitudinal motion of the machinery. The depth of the excavation under construction is changed by turning the soil development equipment of the machinery relative to the axis of the horizontal hinge of its bolting to the tractor. There exist designs where the excavator chain actuator goes laterally when digging the soil, moving along the guides perpendicular to the longitudinal axis of the machinery by a hydraulic cylinder that remains in a parallel position relative to this axis [3].

Significant forces arising from the lateral supply of the actuator to the soil are transmitted to the base tractor and can lead to the periodic loss of the course stability of the machinery. The issues of forming and determining the value of uneven cyclic external load on the actuator during the UEM operating cycle have not yet been scientifically justified and solved.

These kinematic features of the lateral motion of the chain and bar actuator relative to the aft of the tractor cannot minimize and uniform the machine load, primarily due to the uneven thickness of the developed cutting across the width of the excavation.

In case of using milling and throwing, rotor, or screw actuators in universal earthmoving machinery [4,13–15], these shortcomings cannot be eliminated.

Thus, when trenches with a width of 2.2 m are developed, the uneven loading of the drive motor of the UEM rotor actuator reaches 60% (against 20% for conventional trenchers). This leads to a decrease in the engine load factor and, consequently, to incomplete use of its power. The amount of underutilization of power reaches 25%.

When digging the soil for one half-cycle of lateral motion of the actuator (movement from one side wall of the excavation in the soil to another), the cross-sectional area of the cutting across the width of the face is variable—from "zero" to "maximum". Achieving the "maximum" corresponds to the conditions of complete filling of the rotor buckets with soil and, hence, the moment of maximum loading on the actuator.

The impossibility to use the full geometric capacity of the rotor buckets or the volume of the transporting bars of the chain actuator, when they move laterally from one face wall to another during the half-cycle, causes a proportional change in the value of lateral loading on the actuator. For the UEM designs, it has been experimentally established that when the width of the developed excavation is two times larger than the width of the actuator, the bucket filling factor is 0.7, and the energy consumption for the lateral motion of the rotor in the face (the place where the soil is directly developed) reaches 20–30% of the power of its drive. In general, the energy consumption of UEM soil development is 10–15% higher than that of a conventional trencher, which is quite natural [15]. The reasons for this are the imperfection of the kinematics of the cyclic translational and rotational motion of the actuator in the digging mode, soil spills occurring in front of the actuator during its lateral motion, pressing this soil to the excavation walls at the end of each half-cycle. It should be noted that the energy consumption of soil development by UEM rotor actuators is lower compared to the soil development by chain and bar or chain and bucket actuators. The statements determine the direction, purpose, and objectives of the necessary research to create UEM. To solve this problem, scientific work has been performed on the creation of universal continuous rotor earthmoving machinery [15,16].

The purpose of the study is to develop the method for determining the stability of the course of the universal earthmoving machinery operating under cyclic lateral loading.

The objectives of the study are:

- To reveal the physical essence of the process of interaction of the UEM rotary actuator with the soil in the process of digging under the condition of the translational and rotational supply of the actuator;
- To develop a mathematical model of the power load of the UEM operating equipment and the machinery in the process of digging the soil under the condition of the two-hinged, two-link hitch of the actuator at the aft of the machine and on its basis the method of the machinery course stability determination as a decisive factor in ensuring its operability.

In order to achieve the objectives, the article includes the following sections:

- Section 1 introduces the subject and provides an overview of the literature;
- Section 2 presents the description of the used methodology, determining the course stability and the experimental setup used;
- Section 3 presents the results of the experimental studies;
- Section 4 summarizes the work;
- Section 5 describes further research.

2. Materials and Methods

Physical models of UEM operating equipment with both bucketless actuators and bucket rotor ones with centrifugal unloading were mainly used as the research objects. A rotor-vane thrower was used as a tow truck of the developed soil to the edge of the trench.

According to the layout scheme of the UEM operating equipment accepted in this investigation (Figure 2), the development of the soil by the rotor actuator is provided by a combination of three motions: cutting the soil with speed V_c, the longitudinal motion of the machinery at speed V_s, and the translational and rotational lateral motion of the actuator at speed V_{ls}. According to the two-hinge scheme of the actuator hitch on the tractor, its motion in the face with speed V_{ls} is provided by the simultaneous angular motion of two links of the hitch—the intermediate frame and the rotor frame relative to the vertical hinges A and B of its bolting (Figure 2). The developed soil is carried by buckets from the face to the thrower and then to the dump. At a certain frequency of rotation of the rotor, the developed soil is unloaded from the buckets due to the centrifugal forces of inertia. The two-link layout scheme of the operating equipment hitch on the tractor with the individual drive of rotation by the hydraulic cylinders of each link (see Figure 2) enables lateral motions of one of the links to be carried out at the switched off drive of another link motion, to carry out the so-called rotation (additional turn) of an intermediate frame of the actuator.

When digging the soil, there are forces that affect the operating equipment of the machine that are different in nature, power, directions of action vectors, and coordinates of application points (Figure 3). They include: weight loading G_1 from the intermediate frame, weight loading G_2 from the actuator and the frame on which it is installed, components of soil-digging forces—tangential, normal, and lateral soil-digging forces, respectively, P_{01}, P_{02}, P_{03}, horizontal P_h and vertical P_v components of the reaction from throwing the soil into the dump by a rotor thrower, and inertial forces.

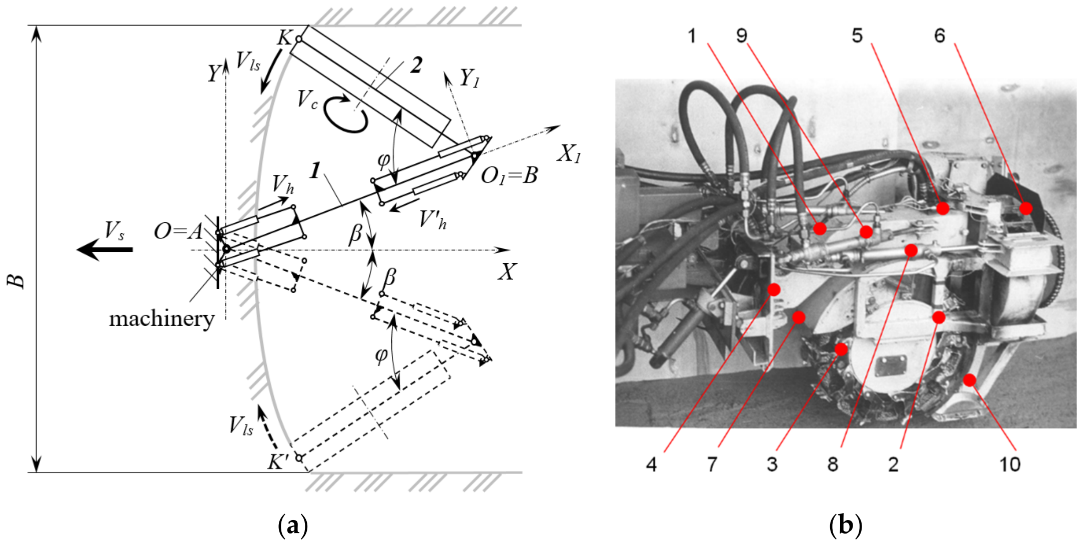

Figure 2. Universal continuous earthmoving machinery (UEM) rotor operating equipment: (**a**) layout scheme; (**b**) physical model of equipment (1—intermediate frame; 2—rotor frame; 3—rotor; 4—vertical hinge aft of the machinery; 5—hinge connecting the rotor frame and the intermediate frame; 6—thrower; 7—rotor housing; 8—hydraulic cylinders of rotor frame rotation; 9—hydraulic cylinders of intermediate frame rotation; 10—sweeping support shoe).

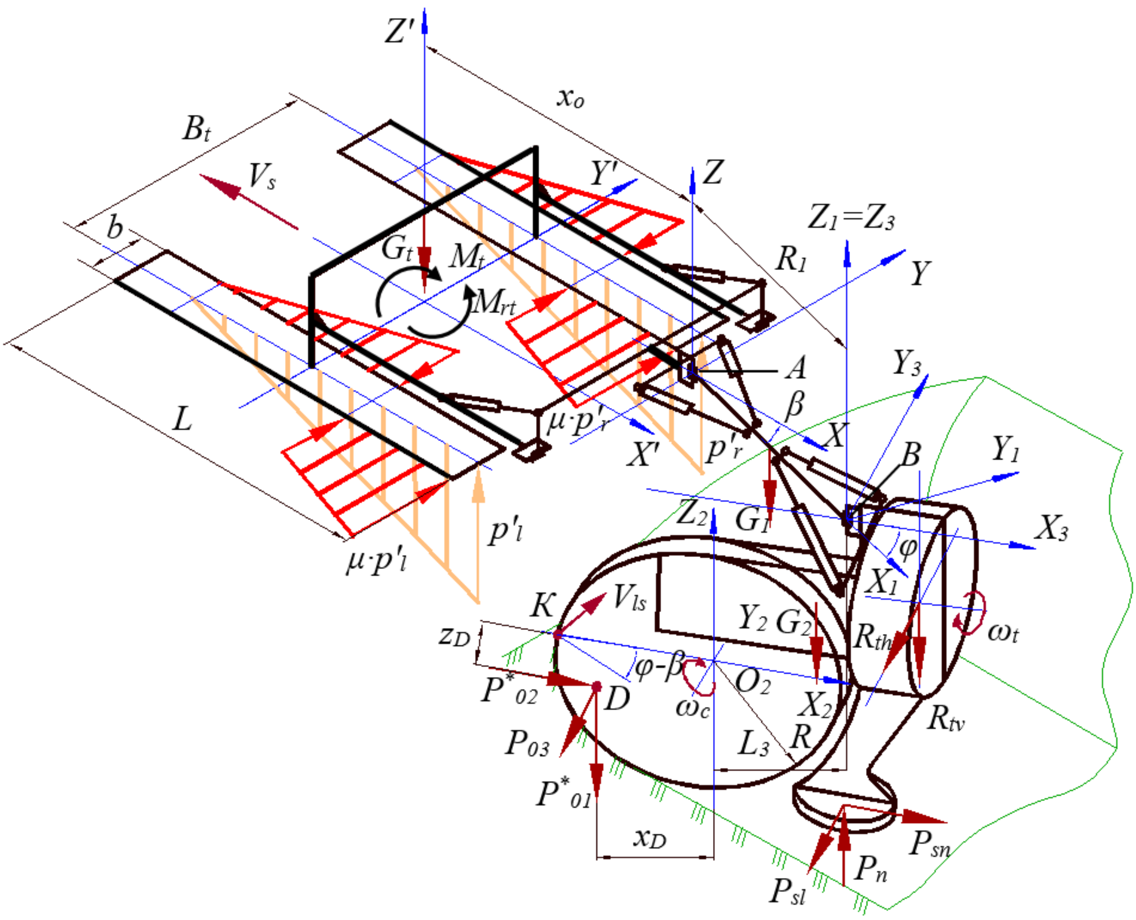

Figure 3. Calculation scheme of power loading of the machinery.

The support shoe of the operating equipment of the machinery from the side of the bottom of the face is affected by the normal force P_n and the force of resistance to the shoe motion on the bottom of the face P_{sn} and P_{sl}.

The load of the operating equipment is transferred aft of the tractor through the vertical bolt hinge. Due to the action of the specified forces, there are the corresponding reactions of R_x, R_y, and R_z (see Figure 3).

The coordinates of the points of the weight loading application, external forces, and their reactions relative to the metal structures of the operating equipment of the machinery are accepted as fixed. However, when digging the soil in the mode of the translational and rotational motion of the actuator, the action of the external forces (as well as moments of forces) relative to the bolting hinge of the operating equipment to the aft of the tractor are variable.

The moment M_t, which turns around the machinery [17] (see Figure 3), is determined by the action of external forces, namely, the force components of the digging of the soil, the forces of inertia, the reactive forces applied to the actuator during digging, the interaction forces of the support shoe with the bottom of the face, and the current dimensions of the shoulders of the application of these forces relative to the bolting hinge of the operating equipment at the aft of the tractor.

The moment of resistance of turning around the machinery M_{rt} [18] (see Figure 3) is caused by the force interaction of the tractor chassis operating equipment with a soil basic surface, taking into account the action of the external load on the tractor when digging the soil, by the nature of distributing the load on a basic surface. As a basic surface, the total contact surface of two tracks of the chassis equipment of the machine with the soil is considered.

When digging the soil, the values of the external forces and moments of forces that turn around the machinery, as well as the moments of resistance to a turn, change over time in both the value and the sign.

The course stability of the machinery is provided when [18]:

$$k_{rcs} \geq \frac{M_{rt}}{M_t} > 1 \tag{1}$$

where k_{rcs} is a reserve ratio of the course stability.

2.1. Determining the Course Stability

The stability of the machinery is characterized by the stability of the operating equipment of the contact of the tractor chassis with the support surface under external loading. The power load of the continuous earthmoving machinery tractor in the digging mode of the soil is determined by the main vector and the main moment of the external forces applied to the bolting hinge of the operating equipment at the aft of the tractor. To determine the moment of resistance of the tractor turn, it is necessary to bring external forces and moments of forces to the center O' of the tractor support surface (Figure 4). Figure 4 should be considered as a supplement to Figure 3.

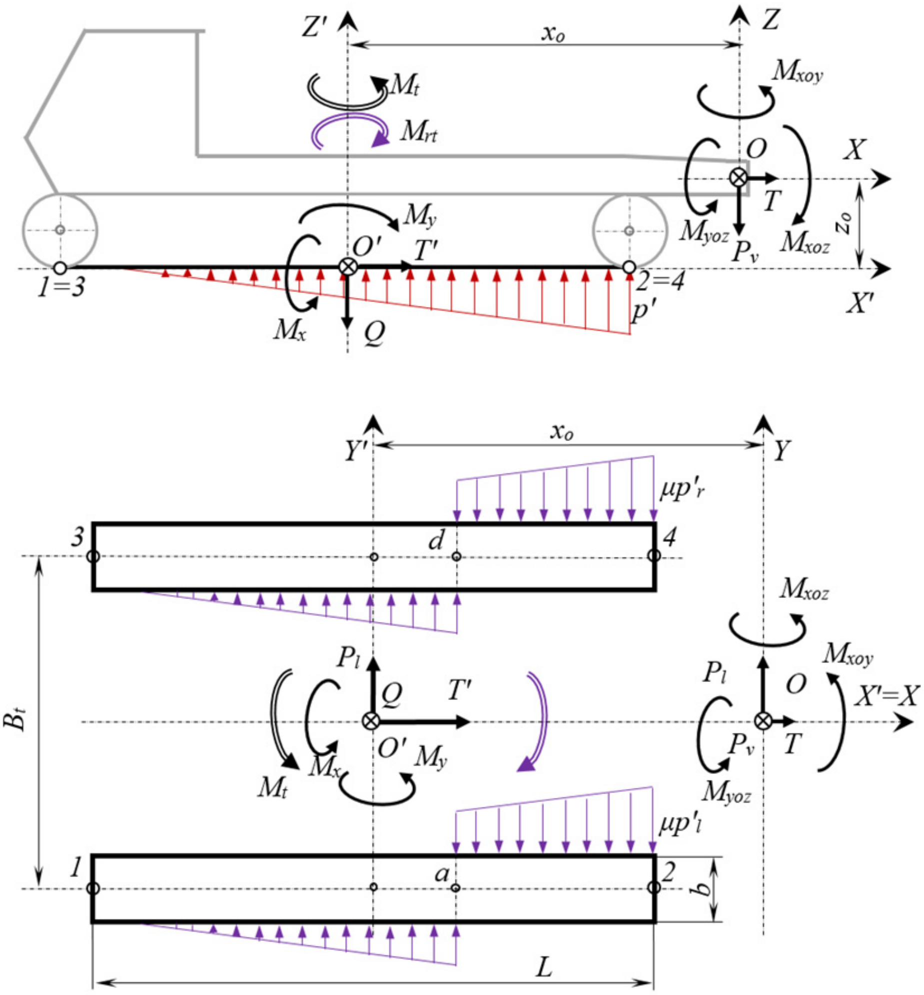

Figure 4. Scheme of determining the moment of resistance of the tractor turn.

The moment acting in the center of the support surface O' (plane $X'O'Y'$), which is also turning, is determined by:

$$M_t = M_{xoy} + P_l \cdot x_o \tag{2}$$

The moment in the vertical longitudinal plane $X'O'Z'$ is determined by:

$$M_y = M_{xoz} + T \cdot z_o + P_v \cdot x_o \tag{3}$$

The moment in the vertical plane parallel to the aft of the machinery $Y'O'Z'$ is determined by:

$$M_x = M_{yoz} - P_l \cdot z_o \tag{4}$$

In the given formulas, M_{xoy}, M_{xoz}, and M_{yoz} are components of the main vector of the moments of forces. T, P_l, and P_v are components of the main vector of forces. x_0 and z_0 are the coordinates of the center of a support surface O' relative to the hinge O at the tractor aft.

The total reduced moment of turn resistance of the caterpillar machinery M_{rt} (Figure 3) consists of the moments of turn resistance of each caterpillar. Under the condition of a trapezoidal diagram of the transverse forces acting on the tractor caterpillar, the moment of resistance of the left and right caterpillars M_{rtl} and M_{rtr} is determined as follows:

$$M_{rtl} = \int_0^{-\frac{L}{2}} \mu \cdot p'_l \cdot x \cdot dx + \int_a^{\frac{L}{2}} \mu \cdot p'_l \cdot x \cdot dx - \int_0^a \mu \cdot p'_l \cdot x \cdot dx \tag{5}$$

$$M_{rtr} = \int_0^{-\frac{L}{2}} \mu \cdot p'_r \cdot x \cdot dx + \int_d^{\frac{L}{2}} \mu \cdot p'_r \cdot x \cdot dx - \int_0^{d} \mu \cdot p'_r \cdot x \cdot dx \quad (6)$$

where p'_l and p'_r are, accordingly, the running loading of the caterpillars on the soil; L is the length of the support surface of the caterpillar; and μ is a coefficient of the turn resistance.

Running $p'_{l(r)}$ loading on the left and right caterpillars in the general case (Figure 3) is determined by:

$$p'_{l(r)} = p_{l(r)} \cdot b, \quad (7)$$

where $p_{l(r)}$ is the pressure on the soil of the corresponding caterpillar and b is the caterpillar width.

The values of the distributed pressure of the machinery on the soil should be calculated as follows:

$$p_l = \frac{p_1 + p_2}{2} + \frac{p_2 - p_1}{L} \cdot x \quad (8)$$

$$p_r = \frac{p_3 + p_4}{2} + \frac{p_4 - p_3}{L} \cdot x \quad (9)$$

where p_1, p_2, p_3, and p_4 are the values of the pressure on the soil at the characteristic points of the support circuit of the machinery (see Figure 4).

In its turn:

$$p_1 = \frac{1}{b \cdot L}\left(\frac{Q}{2} + \frac{M_x}{B_t} - \frac{3 \cdot M_y}{L}\right) \quad (10)$$

$$p_2 = \frac{1}{b \cdot L}\left(\frac{Q}{2} + \frac{M_x}{B_t} + \frac{3 \cdot M_y}{L}\right) \quad (11)$$

$$p_3 = \frac{1}{b \cdot L}\left(\frac{Q}{2} - \frac{M_x}{B_t} - \frac{3 \cdot M_y}{L}\right) \quad (12)$$

$$p_4 = \frac{1}{b \cdot L}\left(\frac{Q}{2} + \frac{M_x}{B_t} + \frac{3 \cdot M_y}{L}\right) \quad (13)$$

In the above-presented formulas, $Q = G_t + P_v$ is the total vertical load on the machinery caterpillars; G_t is the weight of the tractor with attachments; P_v is the vertical load in the bolting hinge of the operating equipment to the aft of the tractor, O point; B_t is the track of the machinery. After solving the above equations by formula:

$$M_{rt} = M_{rtl} + M_{rtr} \quad (14)$$

the total moment of the machinery turn resistance is determined.

The moment that turns the machinery M_t is determined for the digging mode.

The physical nature of the machinery actuator motion from one wall of the excavation to another in the digging mode (half-cycle of the operating process) is characterized by two sections. Both mechanisms of the actuator lateral motion in the face work in the first section. During this period of time, the rotor frame rotates relative to the intermediate frame at an angle of 2φ (see Figure 2). In the second section of the lateral motion, only the mechanism of the intermediate frame rotation works. The rotor frame is locked and it becomes one, as a whole, with the intermediate frame. The time during which the lateral motion of the rotor in the second section of the trajectory occurs is the delay time t_d of rotor frame rotation (time of rotation of the intermediate frame). Ultimately, in a half-cycle, the intermediate frame of the actuator rotates at an angle 2β (see Figure 2).

When digging, the rotor simultaneously develops the soil with the front and side faces of each bucket. External forces acting on the actuator are determined as components of the resistance to digging the soil—tangential, normal, and lateral. It is characteristic for the conditions of digging the soil by other machinery and in other soil conditions [19,20].

In the lateral motion on the side of the rotor, a prism is formed to draw the developed soil. Its presence increases the resistance to the lateral motion of the actuator, especially at the time when the rotor approaches the wall of the excavation in the soil, because at this time, the drawing prism is pressed to the side wall of the excavation. This should be taken into account when the resistance force is determined.

The initial parameters of the research are: the linear dimensions of the operating equipment l_i, the width of the developed excavation B, the hydraulic cylinder speed of extending the rods of the actuator hinge drive (intermediate frame and rotor frame) V_{hyd} and V'_{hyd}, the speed of the longitudinal supply of the machinery V_s, soil cutting V_c, the half-cycle duration of the lateral motion of the intermediate frame t_1 (link 1), the rotor frame t_2 (link 2), and the rotation of the intermediate frame t_d (Figure 2).

When creating external forces acting in the XOZ plane on the rotor actuator during soil digging, let us consider the case of frontal cutting (Figure 5).

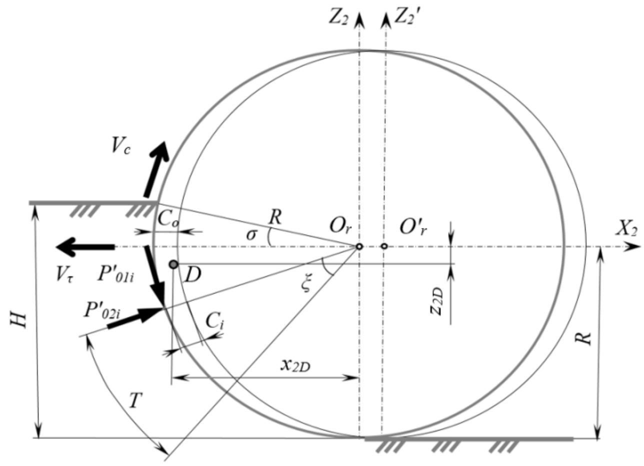

Figure 5. Calculation scheme for determining the resistance to frontal cutting of the soil with the rotor buckets.

The total tangential force of digging the soil with the rotor buckets in this case is determined according to the dependence:

$$P'_{01} = \sum_{i=1}^{n} P'_{01\,i} = b_r \cdot \frac{V_\tau}{V_c} \cdot T \cdot \sum_{i=1}^{n} k_i \cdot cos(\xi \cdot (i-1) - \sigma) \quad (15)$$

where b_r is the rotor width; $T = \frac{2\pi r}{n}$ is a pitch of bucket location on the rotor; n is the number of buckets; R is the radius of the rotor along the edges of the cutters of the installed buckets; k_i is the specific resistance to digging the soil with the i-th bucket; $\varepsilon = \frac{2\pi}{n}$ is an angular pitch of bucket installation; $\sigma = \arcsin\left(\frac{H}{R} - 1\right)$; H is the depth of the excavation under construction; and i is the number of buckets that simultaneously develop the soil.

The normal component of the resistance to digging the soil is:

$$P'_{02} = \psi \cdot P'_{01} \quad (16)$$

where coefficient $\psi = 0.3 \ldots 0.5$ [21] is a coefficient of proportionality (its value is experimentally determined).

Let us consider the case of digging the soil in the XOY plane by the side faces of the rotor buckets (Figure 6).

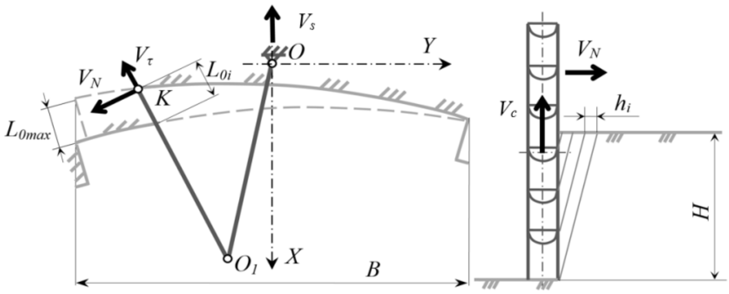

Figure 6. Calculation scheme for determining the resistance to digging the soil by the side faces of the rotor buckets.

The total tangential component of the resistance to digging the soil due to the lateral motion of the actuator in the face is:

$$P''_{01\,i} = \sum_{i=1}^{n} P''_{01\,i} = k \cdot \frac{V_{ls}}{V_c} \cdot T \cdot V_s \cdot t \cdot \cos(\varphi - \beta) \cdot \sum_{i=1}^{n} \cos\,[\xi \cdot (i-1) - \sigma] \tag{17}$$

where k is the specific resistance to digging the soil and t is the current time of lateral motion from the beginning of the half-cycle.

The total lateral component of the soil digging force is:

$$P_{03} = \psi_3 \cdot P''_{01} \tag{18}$$

where ψ_3 is the correction factor determined according to the data of the experimental studies performed in this work.

Let us decompose the total equivalent force of digging the soil with the rotor buckets, not into tangential and normal components, but into horizontal and vertical in the same coordinate system and at the same points of application. Then:

$$P^{*\prime}_{02} = \sum_{i=1}^{n} P_{01\,i} \cdot \sin[\xi \cdot (i-1) - \sigma] + \sum_{i=1}^{n} P_{02\,i} \cdot \cos[\xi \cdot (i-1) - \sigma] \tag{19}$$

$$P^{*\prime}_{01} = \sum_{i=1}^{n} P_{01\,i} \cdot \cos\,[\xi \cdot (i-1) - \sigma] - \sum_{i=1}^{n} P_{02\,i} \cdot \sin\,[\xi \cdot (i-1) - \sigma] \tag{20}$$

In addition to the digging forces, the rotor is affected by the friction forces of the transported soil on the surface of the developed face and the inner surface of the protective guide rotor housing (see Figure 2b), as well as the centrifugal forces of the soil in buckets acting on the structural elements of the actuator rotor.

The horizontal and vertical components of the total centrifugal force of inertia of the transported soil in buckets are determined by:

$$F_h = -\frac{V_c^2}{R}\left(\sum_{i=1}^{n''} m'_i \cdot \cos\,[\xi \cdot (i-1) - \sigma] + \sum_{i=1}^{n'} m'_i \cdot \cos(\xi \cdot i - \sigma)\right) \tag{21}$$

$$F_v = -\frac{V_c^2}{R}\left(\sum_{i=1}^{n''} m'_i \cdot \sin[\xi \cdot (i-1) - \sigma] + \sum_{i=1}^{n'} m'_i \cdot \sin(\xi \cdot i - \sigma)\right) \tag{22}$$

where m'_i is the mass of the soil in each bucket located in the area of the rigidly established cutting perimeter of this bucket.

As a result, the vertical and horizontal components of the friction forces are:

$$P_{h.f} = \frac{V_c^2}{R}\left(f_1 \cdot \sum_{i=1}^{n''} m''_i \cdot \sin[\xi \cdot (i-1) - \sigma] + f_2 \cdot \sum_{i=1}^{n'} m''_i \cdot \sin(\xi \cdot i - \sigma)\right) \tag{23}$$

$$P_{v.f} = \frac{V_c^2}{R}\left(f_1 \cdot \sum_{i=1}^{n''} m_i'' \cdot cos[\xi \cdot (i-1) - \sigma] + f_2 \cdot \sum_{i=1}^{n'} m_i'' \cdot cos(\xi \cdot i - \sigma)\right) \quad (24)$$

where m_i'' is the mass of the soil in the open space of the i-th bucket, which, when moving, is in contact with the undeveloped soil mass.

The total external vertical and horizontal loadings on the actuator when digging and transporting the soil are:

$$P_{01}^* = \left(P_{01}^{*\prime} + F_v + P_{v.f}\right) \cdot \psi_1 \quad (25)$$

$$P_{02}^* = \left(P_{02}^{*\prime} + F_h + P_{h.f}\right) \cdot \psi_2 \quad (26)$$

where ψ_1 and ψ_2 are the empirical correction factors of the actual increase in the vertical and horizontal loadings on the actuator rotor compared with the calculation ones [15].

During the operation of the rotor thrower by means of which the developed soil moves sideways outside the cut excavation, the reactive force R_t affects it from the ejected soil. It is tangentially directed to the ejection trajectory (Figure 7).

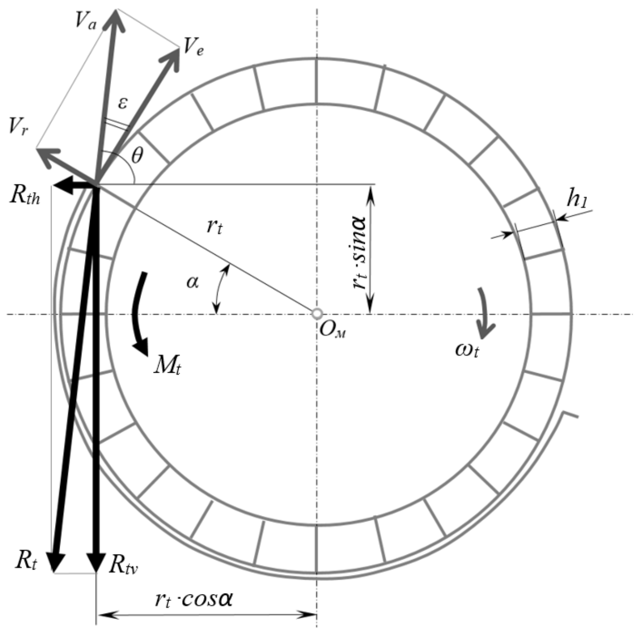

Figure 7. Calculation scheme for determining the loading of the soil thrower.

The force value is determined in accordance with the principle of momentum conservation of momentum in the "thrower-soil" system. In differential form, the reactive force is:

$$R_t = \frac{dm}{dt} \cdot V_a \quad (27)$$

and in integral form it is:

$$R_t = k_l \cdot \gamma \cdot S \cdot V_c \cdot V_a \quad (28)$$

The horizontal R_{th} and vertical R_{tv} components of the specified reactive force R_t are:

$$R_{th} = R_t \cdot cos\theta, \;\; R_{tv} = R_t \cdot sin\theta \quad (29)$$

In the specified formulas, V_a is a vector of the absolute velocity of soil ejection from the thrower; m is the mass of soil that is developed per time unit and is supplied to the thrower; k_l is a coefficient of loosening the soil; γ is the density of the developed soil; S is the total area of cutting that is simultaneously performed by the rotor buckets in the face; V_r is the relative speed of soil motion on the surface of the thrower rotor blade; V_e is the transfer velocity of the soil; and θ is the angle to the horizon of the velocity vector direction of the soil ejection from the thrower. $\theta = 90^\circ - L + \varepsilon$, where $\varepsilon = arctg\frac{V_r}{V_e}$.

In addition, when ejecting the soil on the axis of the thrower rotor rotation, there is the moment of force, the value of which is:

$$M = R \cdot r_t \cdot sin(\alpha + \theta) \tag{30}$$

In the translational and rotational motion of the actuator when digging the soil, the support sweeping shoe is affected by normal force P_n from the bottom of the face and the force of resistance to the shoe motion. Its value is determined by two components: the resistance to the shoe motion P_{sn} along the rotation axis of the soil-development rotor, and the resistance P_{sl} to its lateral motion (Figure 8).

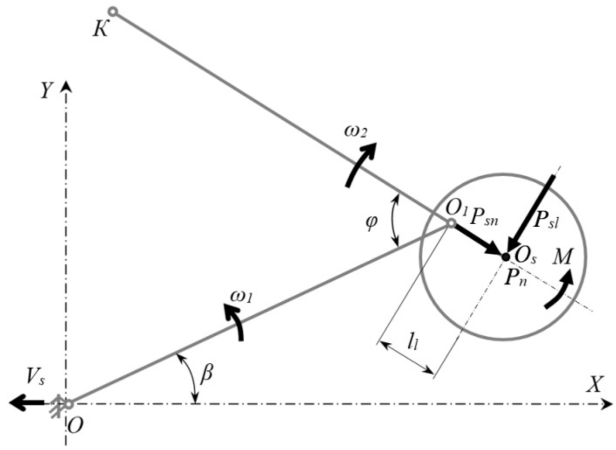

Figure 8. Calculation scheme for determining the loading of the sweeping shoe.

The force P_{sn} is determined by the formula:

$$P_{sn} = P_n \cdot f_1 \tag{31}$$

where f_1 is the coefficient of external friction of the soil.

The force of resistance to the sliding of the shoe support surface on the bottom of the face without crumpling the soil surface at its lateral motion equals:

$$P_{sl} = P_n \cdot (f_1 + k_{ls}) \tag{32}$$

where k_{ls} is the coefficient of lateral support. It takes into account the possible crumpling of the soil by the support surface and its friction on the soil.

When excavating, the support shoe rotates around the axis O_1, which does not pass through the center of its support surface. The moment of the rotation resistance is determined by the formula:

$$M = f_1 \cdot P_n \cdot l_l \tag{33}$$

where l_l is the distance between the axis of rotation O_1 and the center of the shoe support surface.

The dependences obtained are a mathematical model for determining the power loading of the operating equipment of the continuous rotor earthmoving machinery, which develops the soil in a steady mode of translational and rotational supply of the actuator to the face. The parameters of the power loading can be determined at any point of the actuator motion in the face during the operating cycle.

To determine the rotation moment of forces M_t by known methods [20], all external forces that affect the operating equipment in the horizontal plane XOY and in the vertical planes YOZ and XOZ are reduced to point O according to the laws of theoretical mechanics.

It is located aft of the tractor and belongs to the vertical axis OZ of the intermediate frame (see Figure 3). The moments of action of certain external forces are reduced to the same axis OZ. The rotation moment M_t that affects the machinery is calculated after reducing the specified forces and the moments of forces to the center of the tractor support surface O' (see Figure 4).

The peculiarities of the earthmoving machinery operating in the mode of translational and rotational supply of the actuator to the face imply that at the extreme points of its cyclic reciprocating motion, the actuator changes the direction of motion to the opposite one. The motion direction changes during a short period of time. Its duration is equal to the time of a hydraulic valve operation ($t \approx 0.15$ s). This phenomenon should actually be considered as a shock. When considering the course stability of the machinery, shock loadings [22] can be ignored due to their short duration.

Considering the known values M_{rt} and M_t, the determined coefficient of the course stability reserve of the tractor k_{rcs} is an assessment of the course stability of the universal earthmoving machinery as a whole.

2.2. Experimental Setup

Calculations of external forces affecting the UEM operating equipment when digging the soil according to the obtained dependences are possible if the values of correction factors ψ_1, ψ_2, ψ_3 in the formulas of external forces calculation are experimentally determined. The values of the coefficients are conditioned by the peculiarities of digging the soil in the mode of translational and rotational supply of the actuator, which have not been sufficiently studied so far. They include: the complexity of the actuator trajectory when digging the soil and the formation of a drawing prism in the lateral motion of the rotor, pressing this prism to the side wall of the excavation at the end of each half-cycle.

Experimental studies were performed to determine the absolute values of the coefficients by conducting planned experimental studies of the physical model (M1:5) of the UEM operating equipment. The experiments were carried out on a test bench for the physical and mathematical modeling of the continuous earthmoving machinery operating processes (Figure 9).

The test bench is mounted on the ground channel by a tensometric cart made in the form of a spatial truss. It consists of the main frame (1) and a frame (2) moving in the vertical direction of the carriage (3). The actuator under investigation (5) is mounted with a special strain gauge (4) [23] on the carriage. The parameters of the spatial load are fixed simultaneously using the strain gauge (4) during the experimental research. These parameters are the forces on the actuator (traction force T (P_x), vertical force P_v (P_z), lateral force P_l (P_y)) and moments of the specified forces M_{xoy}, M_{xoz}, and M_{yoz} relative to the center of the strain gauge (4) (the hinge to secure the operating equipment on the tractor aft). The directions of the actuator in the up and down motion are provided by a special drive of the carriage. It includes a reversible motor (6), a worm gearbox (7), and a lead screw (8) with a nut fixed in the upper ball bearing (9) of the carriage. To transfer the vertical loading from the carriage to the worm gearbox, the lower end of the lead screw rests on the lower ball bearing (10), rigidly fixed to the frame. The lead screw is connected to the worm gearbox via an elastic finger coupling. In addition to the carriage, the main frame includes: a roller (11) for compacting the model soil with a separate profiling device (12), a pump station of the test bench (13), a station hydraulic panel (14), a starter panel (15), automatic control system units for the actuator tested, and the control panel of the test bench.

To ensure the supply of hydraulic fluid to the actuators of the model, a pump station is used. It includes five pumps (Figure 10). On the control panel of the test bench (Figure 11), there are buttons to turn on the pump station units, mechanisms for raising the carriage, and control and measuring devices to provide the necessary operating mode of the actuators tested.

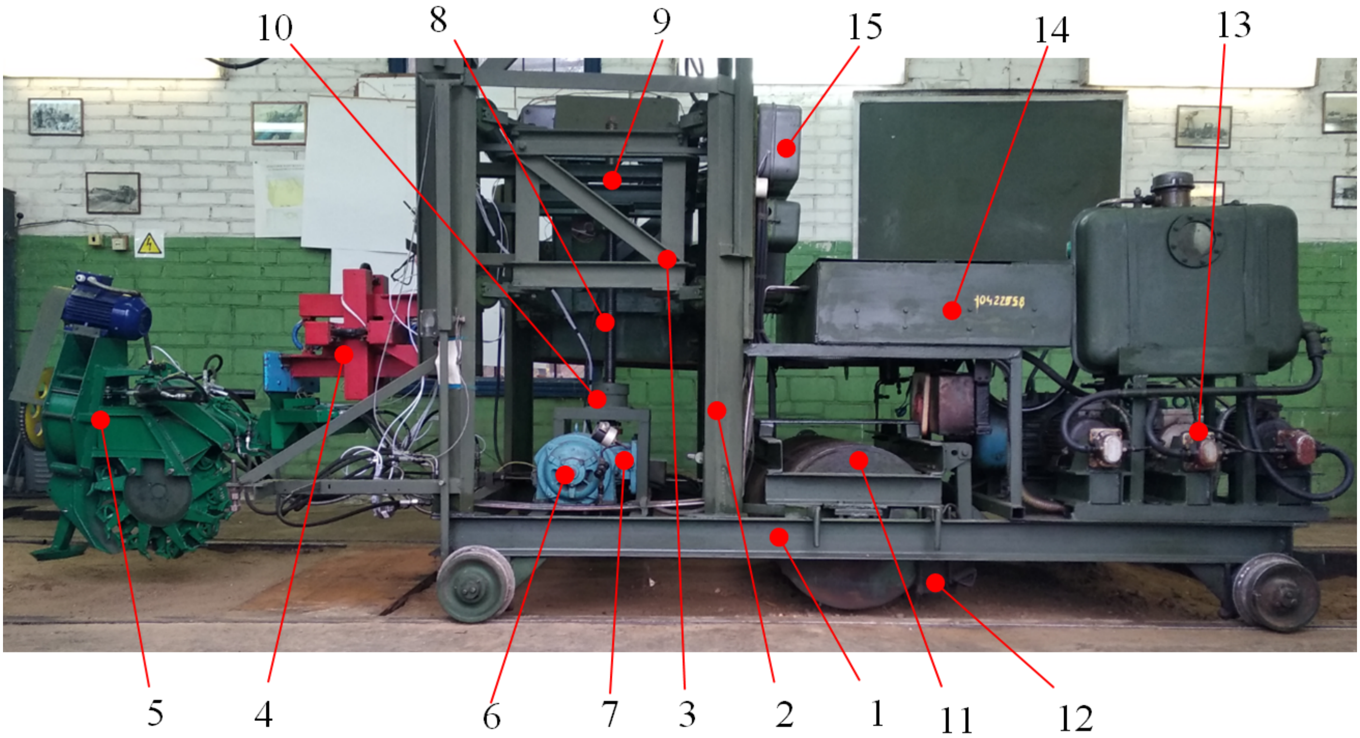

Figure 9. General view of the test bench with a model of the actuator (1—main frame; 2—frame; 3—carriage; 4—strain gauge; 5—actuator; 6—reversible motor; 7—worm gearbox; 8—lead screw; 9—upper ball bearing; 10—lower ball bearing; 11—roller; 12—profiling device; 13—pump station; 14—station hydraulic panel; 15—starter panel).

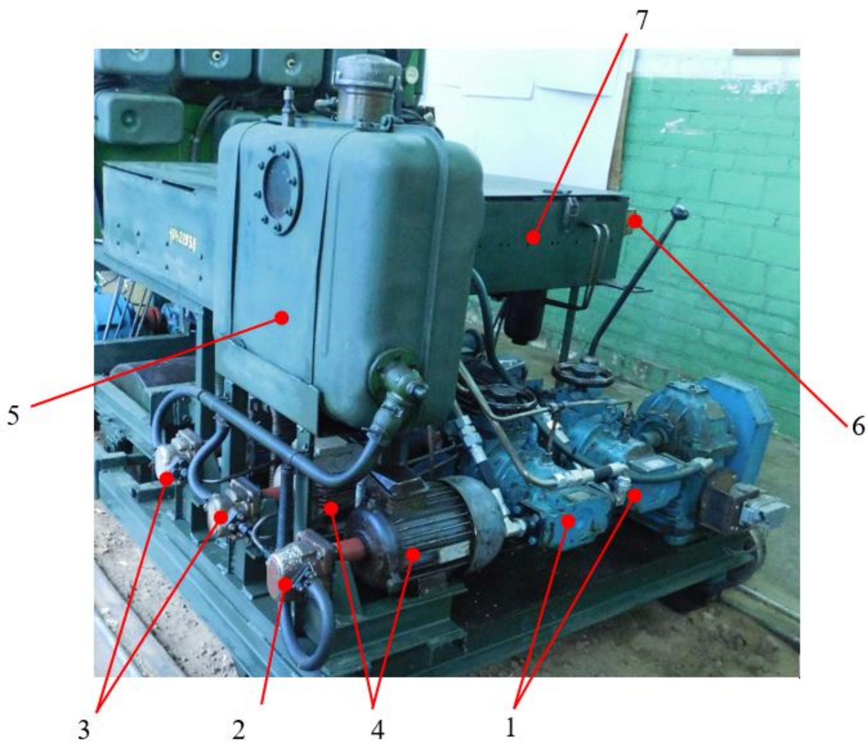

Figure 10. A pump station (1—adjustable pump NAR-40/200; 2—gear pump NCH-6; 3—gear pump NCH-10; 4—electric motor; 5—tank; 6—flow regulator; 7—station hydraulic panel).

Figure 11. A control panel of the test bench.

The automatic control system for the operating process of the operating equipment model provides its automatic work when digging trenches of various width under the conditions of translational and rotational supply of the actuator to the face. The automatic control system consists of two units—the operating unit and the control unit. It is connected to the hydraulic valves to control the drive mechanisms of the actuator.

Using measurement devices installed on the test bench of forces and the moments of forces providing the power loading of the UEM operating equipment when developing the soil, the research aimed to determine the:

- Traction force and vertical and lateral forces on the actuator rotor when digging the soil;
- Torque on the axis of the rotor when developing the excavation;
- Power on the drive shaft of the thrower;
- Total traction forces, vertical and lateral, on the operating equipment reduced to the center of the hinge of the intermediate frame relative to the aft of the machinery;
- Total moments of forces relative to the spatial coordinate system with the center located in the heart of the rotation hinge of the intermediate frame relative to the aft of the machinery.

Ultimately, this enables to the establishment of the laws of these power-loading parameters changes when digging the soil in the mode of translational and rotational supply of the actuator to the face during the operating cycle. It also enables the determination of the values of the studied parameters and operating modes when they are maximum or minimum.

When conducting the research, the main variables that determine the power loading of the actuator, taking into account the previous experimental studies, are the following:

- The speed of supplying the actuator to the face, V_s;
- The soil cutting speed, V_c;
- The speed of the lateral supply of the actuator to the face, V_{ls};
- The soil strength according to the hummer, C;
- The width of the excavation (pit) at the level of the day surface of the soil, B;
- The rotor frame rotation delay time (intermediate frame rotation time when the rotor frame rotation mechanism is stopped at the end of each half-cycle), t_d.

The ranges of factor changes in experimental research are established as follows (in terms of "nature"): V_s = 27–104 m/h; V_c = 6–9 m/s; V_{ls} = 0.7–1 m/s; t_d = 0–1.1 s; C = 5–15; and B = 3.0–4.5 m.

3. Results

The maximum values of the operating equipment load have been established in the maximum productivity mode from the carrying capacity of the actuator while digging an excavation 4.5 m wide and 1.5 m deep in the third category of loamy soils. They are: rotor drive shaft torque M_r = 74 kNm; the main components of the force vector: traction force T = 21 kN, vertical force P_v = 44 kN, lateral force P_l = 85 kN; the components of the main moment of forces brought to the center of the strain gauge: moment of turning forces M_{xoy} = 225 kNm, moment of forces in the vertical plane passing through the machine longitudinal axis M_{xoz} = 72 kNm, and the moment of forces in the plane of the machine aft M_{yoz} = 150 kNm.

The possibility of equalizing and reducing the absolute values of the loads on the UEM operating equipment by improving the machine operating process has been experimentally confirmed. The improvement is ensuring the rotation of the intermediate frame at the end of each half-cycle of the operating process. The necessary turning duration of the intermediate frame has a functional dependence on the real speed of the machine motion.

The regression equations obtained make it possible to perform a comprehensive engineering assessment of the maximum power load of the UEM operating equipment under conditions of changes in the impact factors.

As a result, it has been established that experimentally determined patterns of external load change that affect the actuator when digging the soil confirm the nature of the change in these loads when determining them analytically (Figure 12). The absolute values of the empirical coefficients experimentally determined of the actual increase in the values of lateral, vertical, and horizontal loadings on the rotor compared to the calculated ones are [15]: in the mode without rotation ψ_1 = 0.9–1.5; ψ_2 = 0.7–1.6; ψ_3 = 4.7–5.9; in the mode with rotation φ_1 = 2.6–4.8; φ_2 = 1.5–2.25; φ_3 = 3.0–4.5. The comparison of the absolute values of the lateral loads on the actuator rotor determined experimentally with the calculated values of these loadings (taking into account the coefficient of lateral loading increase) in different modes of operation shows (Figure 12) a sufficient convergence of theoretical and experimental studies. The deviations do not exceed 7%.

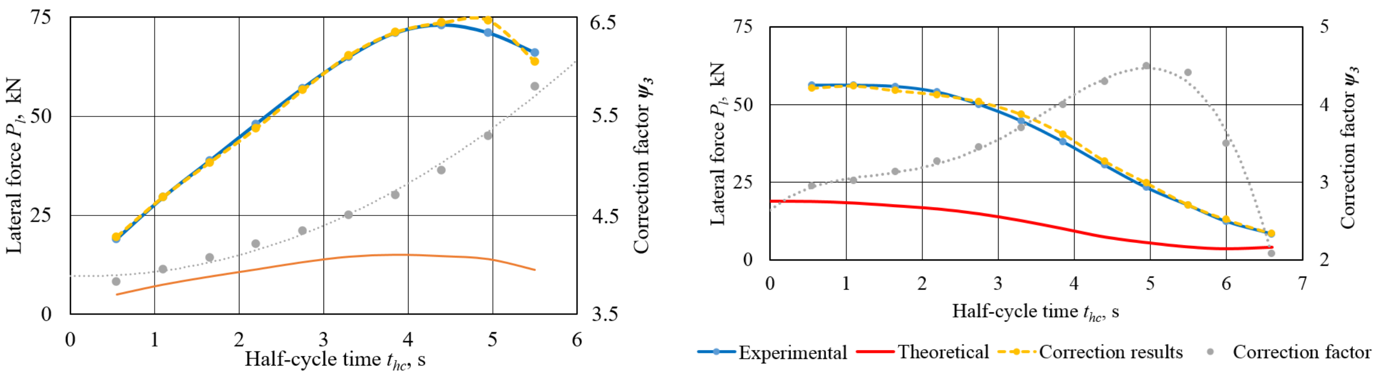

Figure 12. Change of lateral force on the operating equipment of the universal earthmoving machinery during the half-cycle: (**a**) without the intermediate frame rotation; (**b**) with the intermediate frame rotation (C = 15, B = 4.5 m, V_{ls} = 0.7 m/s, V_c = 6 m/s, V_s = 104 m/h).

This indicates the objectivity of taking into account the physical characteristics of the soil by the UEM actuator in the analytical research, and in the definition of external loadings determining the moments of forces that rotate around the machinery in the process of digging the soil.

4. Conclusions

The article solves the important scientific and technical task of developing and experimentally confirming the adequacy of the developed calculation methodology and ensuring the course stability of the universal earthmoving machine in the process of digging the soil:

1. The calculation scheme for determining the power load of the UEM with a two-link system of lateral supply of the operating equipment to the face in the mode of digging the soil with maximum productivity has been substantiated and developed for the first time. The dependencies to define the external forces that determine the machinery course stability in the translational and rotational supply mode of the actuator have been obtained.
2. The factors whose change determines the value of the loading on the UEM operating equipment in the mode of digging the soil have been determined. These include the width and the depth of the excavation under construction, the speed of the longitudinal motion of the machinery along the face, the speed of the lateral supply to the face of each of the two links of the operating equipment, the soil strength according to the hummer of the Ukrainian State Road Scientific and Research Institute, and the duration of the intermediate frame rotation of the operating equipment at the end of each half-cycle of the operating process.
3. The mathematical models of the power loading of the UEM operating equipment and for determining the machinery course have been created in the process of digging the soil. They are based on taking into account the physical features of the digging process in the mode of translational and rotational supply of the rotor actuator to the face. It enables the calculation of the machinery course stability in the operating mode with sufficient accuracy.
4. The developed method for determining the stability of the UEM course can be used when creating the industrial samples of trenching earthmoving machinery.

5. Further Research

Further research is required to determine the ways of reducing the uncontrolled collapse (spilling) of the soil in front of the excavation actuator in the process of the soil as the main factor in the formation of resistance forces during the cyclic lateral movement of the rotor in the face.

Author Contributions: Conceptualization, V.M. (Volodymyr Musiiko), A.K. and M.T.; methodology, V.M. (Volodymyr Musiiko), A.K. and M.T.; validation, M.S., J.M. and V.M. (Vasyl Mateichyk); formal analysis, V.M. (Volodymyr Musiiko), V.M. (Vasyl Mateichyk), M.T. and M.S.; investigation, A.K., M.T. and V.M. (Volodymyr Musiiko); resources, V.M. (Volodymyr Musiiko), V.M. (Vasyl Mateichyk), M.T. and A.K.; data curation, M.S. and J.M.; writing—original draft preparation, A.K., J.M., V.M. (Vasyl Mateichyk) and M.S.; writing—review and editing, J.M., M.S. and V.M. (Vasyl Mateichyk); visualization, J.M, A.K. and V.M. (Volodymyr Musiiko); supervision, M.S., M.T. and V.M. (Vasyl Mateichyk); project administration, M.T., V.M. (Vasyl Mateichyk) and M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lemu, H.; Kejela, D. Design and modelling of a light duty trencher for local conditions. *Adv. Sci. Technol. Res. J.* **2018**, *12*, 303–311. [CrossRef]
2. Mikhlevskiy, A.I.; Kavalerov, A.A.; Sidorov, K.I.; Lisnovskiy, B.G.; Kvach, A.A.; Suchenko, V.G.; Ivanov, I.I.; Guzenko, N.N.; Redko, D.L.; Shevchenko, G.V.; et al. Trench Digging Machinery (USSR). Copyright certificate № 184732, 21 July 1966; 5p. (In Russian)
3. Musiiko, V.D.; Koval, A.B. *Theory and Creation of Innovative Continuous Earthmoving Machinery*, 2nd ed.; Lyudmyla: Kiyv, Ukraine, 2018; p. 280. (In Ukrainian)
4. The Applicant Unit Rig et Equipment Co. Dispositif D'oscillation Transversale Pour Excavatrice-Chargeuse. Patent 2318277, 11 February 1977.
5. Alvarez Grima, M.; Verhoef, P.N.W. Forecasting Rock Trencher performance using fuzzy Logic11a shorter version of this paper was presented at the 36th US rock mechanics symposium, New York. *Int. J. Rock Mech. Min. Sci.* **1999**, *36*, 413–432. [CrossRef]
6. Vu, M.T.; Jeong, S.-K.; Choi, H.-S.; Oh, J.-Y.; Ji, D.-H. Study on down-cutting ladder trencher of an underwater construction robot for Seabed Application. *Appl. Ocean Res.* **2018**, *71*, 90–104. [CrossRef]
7. Vu, M.T.; Choi, H.-S.; Kim, J.-Y.; Tran, N.H. A study on an underwater tracked vehicle with a ladder trencher. *Ocean Eng.* **2016**, *127*, 90–102. [CrossRef]
8. Hu, K.; Cheng, K. Dynamic modelling and stability analysis of the articulated tracked vehicle considering transient track-terrain interaction. *J. Mech. Sci. Technol.* **2021**, *35*, 1343–1356. [CrossRef]
9. Benoit, O.; Gotteland, P.; Quibel, A. Prediction of trafficability for tracked vehicle on broken soil: Real size tests. *J. Terramechanics* **2003**, *40*, 135–160. [CrossRef]
10. Rahman, A.; Mohiuddin, A.K.; Hossain, A. Performance measurements of a tracked vehicle system. *Int. J. Automot. Technol.* **2011**, *12*, 503–512. [CrossRef]
11. He, R.; Sandu, C.; Khan, A.K.; Guthrie, A.G.; Schalk Els, P.; Hamersma, H.A. Review of terramechanics models and their applicability to real-time applications. *J. Terramechanics* **2019**, *81*, 3–22. [CrossRef]
12. Kim, S.-H.; Lee, Y.-S.; Sun, D.-I.; Lee, S.-K.; Yu, B.-H.; Jang, S.-H.; Kim, W.; Han, C.-S. Development of bulldozer sensor system for estimating the position of Blade Cutting Edge. *Autom. Constr.* **2019**, *106*, 102890. [CrossRef]
13. Bandurov, V.M.; Baranov, I.M.; Goryachev, V.F.; Zhabin, V.F.; Kakusha, N.I.; Kavalerov, A.A.; Kochev, N.I.; Lobanov, N.V.; Maksimov, V.A.; Medovnikov, V.P.; et al. Rotor Actuator of Universal Earthmoving Machinery (USSR). Copyright certificate № 905387, 15 February 1982; 3p. (In Russian)
14. Farmer, I.W. Performance of chain trenchers in mixed ground. *J. Constr. Eng. Manag.* **1996**, *122*, 115–118. [CrossRef]
15. Koval, A.B. Determining the Conditions for Ensuring the Course Stability of Universal Earthmoving Machinery. Ph.D. Thesis, National Transport University, Kyiv, Ukraine, 2014; 218p. (In Ukrainian)
16. Koval, A.B. Physical features of loading formation on the actuators of universal earthmoving machinery. In *Col. of Scient. Papers Construction. Materials Science. Mechanical Engineering. Intensification of the Operating Processes of Construction and Road Machinery*; Koval, A.B., Ed.; Series: Lifting-and-Transport, Construction and Road Machinery and Equipment; SHEI "PSACEA": Dnepropetrovsk, Ukraine, 2014; Volume 79, pp. 125–132. (In Ukrainian)
17. Dombrovskiy, N.G.; Mayevskiy, A.G.; Gomozov, I.M.; Gilis, V.M. *Theory and Calculation of the Caterpillar Mover of Earthmoving Machinery*; Technics: Kyiv, Ukraine, 1970; 192p. (In Russian)
18. Guskov, V.V.; Opeiko, A.F. *Theory of Rotation of Caterpillar Machinery*; Mechanical Engineering: Moscow, Russia, 1984; 168p. (In Russian)
19. Sitorus, P.E.; Ko, J.H.; Kwon, O.S. Parameter study of chain trenching machines of underwater construction robots via analytical model. In Proceedings of the OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, USA, 19–23 September 2016. [CrossRef]
20. Kim, J.; Kwon, O.S.; Hai, N.L.; Ko, J.H. Study on the design of an underwater chain trencher via a genetic algorithm. *J. Mar. Sci. Eng.* **2019**, *7*, 429. [CrossRef]
21. Zelenin, A.N. *Basics of Soil Destruction by Mechanical Means*; Mechanical Engineering: Moscow, Russia, 1968; 375p. (In Russian)
22. Garbuzov, Z.Y.; Ilgisonis, V.K.; Mutushev, G.A.; Naret, G.B.; Podborskiy, L.E.; Uspenskiy, V.P. Continuous digging machinery. In *Constructions and Calculations*; Ye, L., Podborskiy, M., Eds.; Mechanical Engineering: Moscow, Russia, 1965; 275p. (In Russian)
23. Dmytrychenko, M.F.; Bilyakovych, M.O.; Musiiko, V.D.; Koval, A.B.; Voshchak, Y.V.; Kucher, O.P.; Horkovenko, O.V. Universal Strain Gauge and Method for Determining Force Parameters of Spatial Loadings of Earthmoving Machinery Actuators. Patent № 111690, 25 May 2016. (In Ukrainian)