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Research of the dynamics of the process of excavating the soil with the additional slope board of the bulldozer on the caterpillar track

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ABSTRACT

The purpose of the research is to determine the conditions for maintaining the course stability of the bulldozer on the caterpillar track (hereinafter referred to as the term "caterpillar") in the process of excavating the soil with the slope board. The paper presents mathematical model of the process of operation of the caterpillar bulldozer with the slope board, taking into account its main parameters: 1) parameters of the slope board and its installation angles; 2) parameters of the base machine; 3) dynamic parameters of the bulldozer with the slope board; 4) parameters of the soil. Based on the developed model, using the computer modelling method in Mathcad Prime 3.0 program, a hodograph of the maximum force applied on the slope board of the caterpillar bulldozer was built, which made it possible to determine the maximum allowable force applied on the slope board, taking into account the retention of the course stability.

KEYWORDS

Caterpillar bulldozer, Slope board, Course stability

1. INTRODUCTION

The machine with a slope board is used in road construction, planning of meliorative lands and landscape design. Slope boards are used to increase the productivity of work, efficient use of engine power and increase in the technological capabilities of earthmoving machines. [1] The slope board is mounted on the push arm of the bulldozer [2] (Figure 1).

The constructive difference between the additional slope board and the main blade of the bulldozer is its installation on the side, outside the support surface of the base machine and the ability to change the angle of tilt in the vertical plane and the angle of capture in the horizontal plane [3, 4]. Figure 2 shows the process of cutting the soil shavings with the slope board of the bulldozer and the angles of installation of the slope board (γ, β).

The process of planning with a slope blade occurs at different angles of capture and tilt. These angles affect digging resistance and course stability, these factors affect energy consumption, productivity and quality of work [5].

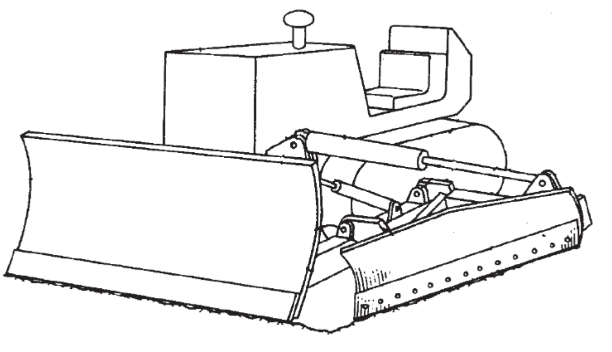

Figure 1: Installation scheme of the slope board on the bulldozer's push arm

2. MATHEMATICAL MODEL OF THE BULLDOZER WITH THE SLOPE BOARD

In general, the mathematical model of the working process of the caterpillar bulldozer with the additional slope board [6] is shown in the figure 3, which takes into account:

1) geometric parameters of the slope blade (B_A and H_A – width and height, m), weight of the slope board $m_{s.b.}g$, N ($m_{s.b.}$ – mass of the slope board, kg; g=9.81 m/s^2);
2) angles of installation of the slope board (β, γ, Δ – respectively, the angles of capture, tilt and depth;
3) the parameters of the base machine, taking into account the influence of the main blade and slope board ($m_b g$ – the weight of the machine, N; the contact area of the support surface of the caterpillar track, m^2 (further, the term "caterpillar" is used), K – gauge, m; v_b – the speed of the bulldozer, m/s; N_{en} – the power of the bulldozer's engine, W; P_{k1} – the pull force of the bulldozer in the first gear, N; $N_{c.p.}$ - the resulting vertical reaction force from the ground to the caterpillars, N; $x_{c.p.}$, $y_{c.p.}$ – the coordinates of the force $N_{c.p.}$, m; $q_1(n)$, $q_2(n)$ - the dependence of the pressure on the caterpillar from the coordinate η ($0 \le \eta \le l_{base}$), respectively on the 1st and 2nd caterpillar, Pa; l_{base} - caterpillar base (Figure 4), m; R_A, R_B, R_C, R_D - vertical reactions from the caterpillars to the base surface – soil, N; P_{f1}, P_{f2} – the forces of resistance to movement on the 1st track and the 2nd track, respectively, N; φ_{a1max}, φ_{b1max}– the maximum value of the traction coefficient for the 1st caterpillar, respectively in the transverse and longitudinal direction (in the direction of movement of the machine) [7], φ_{a2max}, φ_{b2max} - the same, but for the 2nd caterpillar [7]; T_{ai}, T_{bi} – the transverse and longitudinal traction force of the caterpillar with the ground, accordingly, N, where i is the index of the caterpillar; T_{aimax}, T_{bimax} is the maximum traction force of the caterpillar with the ground, respectively, in the transverse and longitudinal direction, N [7]; M_i is the moment of traction (friction) of the caterpillar with the ground, Nm; a, b are the coordinates of the sliding center, m;
4) dynamic parameters of the bulldozer with the additional slope board (P_x, P_y, P_z– components of the resistance force to digging with the additional slope board, respectively, along the axes x, y, z, N; α_1 – the angle of the direction of action of the force P on the horizontal plane (Figure 4); N_x – the resistance force to the movement of the soil drawing prism on the main blade;
5) parameters of the soil (V_A, V_M – the volume of the soil drawing prism, respectively, on the slope board and main blade, m^3; ρ is the soil's density of the drawing prism, kg/m^3; k is the coefficient of resistance of the soil to cutting, Pa; μ_1 is the coefficient of metal on the soil friction; f is the coefficient of resistance to movement of the base machine; C_s is the adhesion of soil, Pa; φ_s is the internal friction angle of soil).

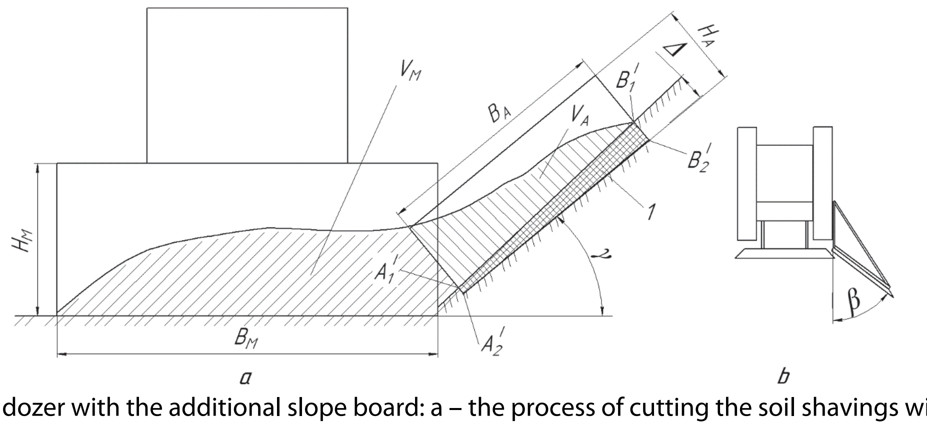

Figure 2: The bulldozer with the additional slope board: a – the process of cutting the soil shavings with the slope board; b – the angle of capture of the slope board – β. 1 – the soil shavings; B_M and H_M – the width and height of the main blade; B_A and H_A – the width and height of the additional slope board; γ - the tilt angle; Δ – the depth angle; V_M, V_A, – the volume of the soil drawing prism, respectively, on the main blade and on the additional slope board; A'_1, A'_2, B'_1, B'_2, – the projection points of the soil shavings

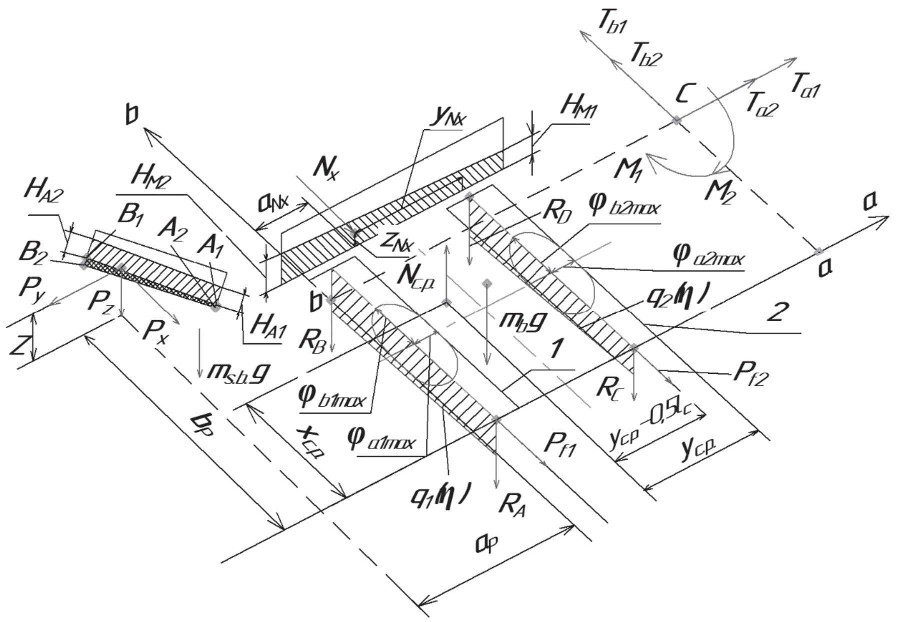

Figure 3: Mathematical model of the operation of the caterpillar bulldozer with the additional slope board: 1 – the first (left) caterpillar; 2 – the second (right) caterpillar; H_{A1}, H_{A2}– the height of the trace from the soil drawing prism on the slope board, respectively, from points A_1 and B_1, m; H_{M1}, H_{M2}– height of the trace from the soil dragging prism on the main blade, respectively, to the left and right in the direction of the bulldozer's movement, m; a_P, b_P, z – coordinates of the application of forces P_x, P_y, P_z, m [6, 8]; a_{Nx}, z_{Nx}, y_{Nx}– coordinates of the application of force N_x, m [6]

To maintain the course stability of the bulldozer with the slope board and when designing the slope board, it is important to determine the limit (maximum) force applied on the slope board of the bulldozer.

We will determine the limit force *P* applied on the slope board under the action of which the bulldozer turns passively, taking into account the forces of resistance to movement (P_{f1}, P_{f2}) and the resistance force from the movement of the drawing prism on the main blade (N_x). To draw a scheme of the action of forces and determine the limit force *P*, we took into account: 1) The traction forces T_a, T_b and the traction moment *M*, which depend on the coordinates of the sliding center (*a; b*) [9, 10]; 2) The system of equilibrium equations of the caterpillar bulldozer when the force is applied at the edge of the main blade [9, 11].

The scheme for determining the limit force *P* applied on the slope board under the action of which the passive rotation of the bulldozer occurs is shown in Figure 4.

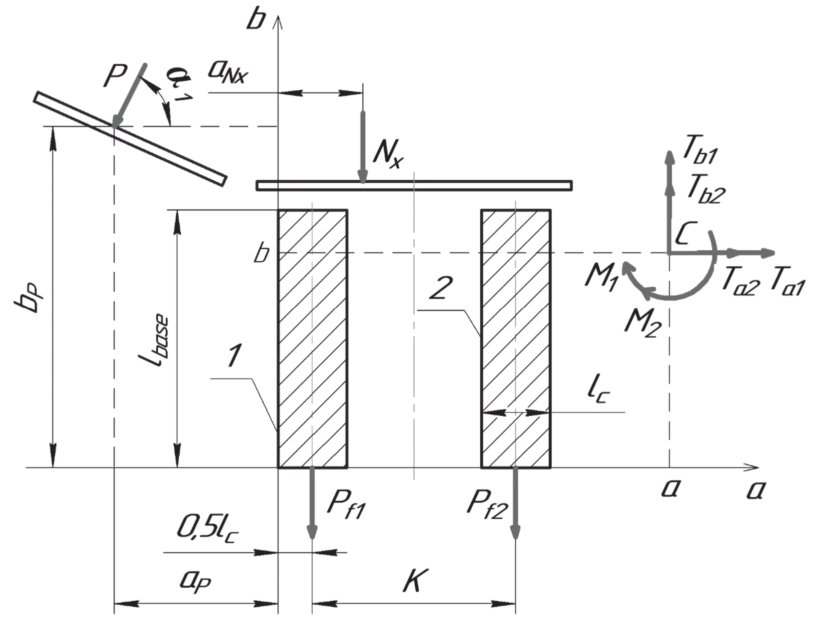

Figure 4: A scheme for determining the limit force P applied on the slope board under the action of which a passive turn of the bulldozer occurs: 1 – the first (left) caterpillar; 2 – the second (right) caterpillar

We will make up the equilibrium equations of the bulldozer with the slope board (Figure 4):

$$-Pcos\alpha_1 + T_{a1} + T_{a2} = 0 \quad (1)$$

$$-Psin\alpha_1 - N_x - P_{f1} - P_{f2} + T_{b1} + T_{b2} = 0 \quad (2)$$

$$Psin\alpha_1\left(a_P + a\right) + Pcos\alpha_1\left(b_P - b\right) + P_{f1}\left(a - \frac{l_c}{2}\right) + P_{f2}\left(a - K - \frac{l_c}{2}\right) + N_x\left(a - a_{Nx}\right) - M_1 - M_2 = 0 \quad (3)$$

where

$$T_{a1} = -\int_0^{l_{base}}\int_0^{l_c} q_1(\eta)\cdot\varphi_{a1max}\cdot\frac{b-\eta}{\sqrt{(a-\xi)^2+(b-\eta)^2}}d\xi d\eta \quad (4)$$

$$T_{a2} = -\int_0^{l_{base}}\int_K^{K+l_c} q_2(\eta)\cdot\varphi_{a2max}\cdot\frac{b-\eta}{\sqrt{(a-\xi)^2+(b-\eta)^2}}d\xi d\eta \quad (5)$$

where P_{f1}, P_{f2} are the forces of resistance to movement on the 1st caterpillar and the 2nd caterpillar, respectively, N:

$$P_{f1} = f\left(R_A + R_B\right) \quad (6)$$

$$P_{f2} = f\left(R_C + R_D\right) \quad (7)$$

f – the coefficient of resistance to the movement of the bulldozer, we accept *f*=0,07;

$$T_{b1} = \int_0^{l_{base}}\int_0^{l_c} q_1(\eta)\cdot\varphi_{b1max}\cdot\frac{a-\xi}{\sqrt{(a-\xi)^2+(b-\eta)^2}}d\xi d\eta \quad (8)$$

$$T_{b2} = \int_0^{l_{base}}\int_K^{K+l_c} q_2(\eta)\cdot\varphi_{b2max}\cdot\frac{a-\xi}{\sqrt{(a-\xi)^2+(b-\eta)^2}}d\xi d\eta \quad (9)$$

$$M_1 = \int_0^{l_{base}}\int_0^{l_c} q_1(\eta)\cdot\varphi_{a1max}\cdot\frac{(b-\eta)^2}{\sqrt{(a-\xi)^2+(b-\eta)^2}}d\xi d\eta + \int_0^{l_{base}}\int_0^{l_c} q_1(\eta)\cdot\varphi_{b1max}\cdot\frac{(a-\xi)^2}{\sqrt{(a-\xi)^2+(b-\eta)^2}}d\xi d\eta \quad (10)$$

$$M_2 = \int_0^{l_{base}}\int_K^{K+l_c} q_2(\eta)\cdot\varphi_{a2max}\cdot\frac{(b-\eta)^2}{\sqrt{(a-\xi)^2+(b-\eta)^2}}d\xi d\eta + \int_0^{l_{base}}\int_K^{K+l_c} q_2(\eta)\cdot\varphi_{b2max}\cdot\frac{(a-\xi)^2}{\sqrt{(a-\xi)^2+(b-\eta)^2}}d\xi d\eta \quad (11)$$

In the system of equations (1-3), the force *P* and the coordinates of the sliding center (*a, b*) are unknown. It is important to note that for the given direction of action of force *P* (angle a_1), only one sliding center (*a, b*) corresponds [9, 10]. To determine the force *P*, it is necessary to solve the system of equations (1-3) with known parameters and a given angle a_1 relatively to the coordinates *a, b* and force *P* [9]. The solution of the system of equations (1-3) relatively to the coordinates *a, b* and force *P* was carried out numerically in the Mathcad Prime 3.0 program.

Determination of the limitation of the values P_x, P_y by the limit of traction of the caterpillars to the ground. From formulas (1, 2) we derive $Pcosa_1$ and $Psina_1$:

$$Pcos\alpha_1 = T_{a1} + T_{a2} \quad (12)$$

$$Psin\alpha_1 = T_{b1} + T_{b2} - N_x - P_{f1} - P_{f2} \quad (13)$$

The values of P_x, P_y by the traction limit must satisfy the following inequalities:

$$P_x \le Psin\alpha_1 \quad (14)$$

$$P_y \le Pcos\alpha_1 \quad (15)$$

To compare P_x and $Psin\alpha_1$, P_y and $Pcos\alpha_1$ we accept:

$$\alpha_1 = 90^0 \text{ in case of } P_y = 0 \text{ H}$$

$$\alpha_1 = arctg\left(\frac{P_x}{P_y}\right) \text{ in case of } P_y > 0H$$

Formulas (14, 15), taking into account formulas (12, 13), will take the form:

$$P_x \le T_{b1} + T_{b2} - N_x - P_{f1} - P_{f2} \tag{16}$$

$$P_y \le T_{a1} + T_{a2} \tag{17}$$

To maintain course stability, the following conditions must be met also:

1)

$$T_{a1} \le T_{a1max} \tag{18}$$

$$T_{a2} \le T_{a2max} \tag{19}$$

$$T_{b1} \le T_{b1max} \tag{20}$$

$$T_{b2} \le T_{b2max} \tag{21}$$

In order for the process of excavating (digging) with the slope board of the bulldozer to take place, it is necessary that the pull force developed by the bulldozer in 1st gear was greater than or equal to the sum of external resistance forces:

$$P_x + N_x + P_{f1} + P_{f2} \le P_{k1} \tag{22}$$

where P_{k1} is the pull force developed by the bulldozer in the 1st gear:

$$P_{\mathrm{k}1} = \frac{\eta_{\mathrm{ce}} \cdot N_{en}}{v_{\mathrm{b}}} \cdot (1 - k_r) \tag{23}$$

η_{ce} - coefficient of efficiency, η_{ce}=0.75; N_{en}– engine power, W; v_b – speed of the bulldozer in the 1st gear, m/s; k_r – coefficient of reserved pull force to account for changes in the value of the coefficient of soil resistance to cutting and other factors, k_r =0.2.

Taking into account the formula (22), we determine the limit of the P_x value by the limit of the available pull force of the bulldozer in the 1st gear:

$$P_x \le P_{k1} - N_x - P_{f1} - P_{f2} \tag{24}$$

2)

$$\frac{\varphi_b^2}{\varphi_{bmax}^2} + \frac{\varphi_a^2}{\varphi_{amax}^2} = 1 \ (\varphi_{\mathrm{bmax}} > \varphi_{\mathrm{amax}}) \tag{25}$$

– canonical equation of the traction (friction) ellipse [12, 13, 14, 15], where φ_b is the current value of the longitudinal traction coefficient; φ_{bmax} is the maximum value of the longitudinal traction, when a longitudinal force is applied in the center of the pressure of the machine; φ_a is the current value of the transverse traction coefficient; φ_{amax} is the maximum value of the transverse traction, when a transverse force is applied in the pressure center of the machine.

The course stability of a bulldozer with a slope board will be maintained if the conditions (16-21, 25) are met. Also, the bulldozer with the slope board will perform the process of excavating (digging) with the slope board, if condition (24) is met.

3. DETERMINATION OF THE LIMIT FORCE ON THE SLOPE BOARD, TAKING INTO ACCOUNT THE RETENTION OF THE COURSE STABILITY OF THE BASE MACHINE

To determine the values of $P(a_1)$, we substitute the initial data into the system of equations and then solve this system of equations. We will construct hodographs of the limit force P, which can be applied on the slope board, while introducing the following assumptions:

1) hodograph $P(a_1)$ without taking into account the influence of P on the distribution of pressure on the caterpillars and on the traction coefficients (only the weight and geometric parameters of the bulldozer with the slope board are taken into account);
2) hodograph $P''(\alpha 1)$, taking into account the influence of $P_x^{'}$, $P_y^{'}$, $P_z^{'}$, weight and geometric parameters of the bulldozer with the slope board on the distribution of pressure on the caterpillars and on the traction coefficients. The values $P_x^{'}$, $P_y^{'}$, $P_z^{'}$ are calculated using the following formulas:

$$P_x^{'} = Psin\alpha_1 \quad (26)$$

$$P_y^{'} = Pcos\alpha_1 \quad (27)$$

in case of $0^0 \le \alpha_1 \le 180^0$: we calculate $P_z^{'}$ by formula:

$$P_z^{'} = Psin\alpha_1 \cdot sin\alpha \cdot cos\alpha \quad (28)$$

where α is the cutting angle of the slope board's blade, α = 60⁰,

in case of $180^0 < \alpha_1 < 360^0$ $P_z^{'} = 0$

where *P* is the value of the limit force applied on the slope board, the values of *P* were taken from the first hodograph *P(α1)*.

As a result of computer modelling in the Mathcad Prime 3 program, hodographs of the limit force *P,* which is applied on the slope board, were drawn (Figure 5). Initial data for the drawn hodographs:

1) parameters of the caterpillar bulldozer (CHETRA T9.01; $m_b{\cdot}g$=198 kN; N_{en}=110 kW; v_b=1.05 m/s; P_{k1}=63 kN; width of the main blade, B_M=3.16 m; caterpillar width, l_c=0.56 m; caterpillar base, l_{base}=2.47 m; caterpillar gauge, *K*=1.75m; caterpillar's link pitch, t_c=0.19m; height of caterpillar grouser, h_c=0.055m);
2) parameters of the slope board ($m_{s.b.}g$=7.9 kN; B_A=1.334 m, H_A=0.467 m, $\beta=90^0$, $\gamma=0^0$, N_x=0kN; coordinates of the application of force *P* on the slope board a_P =1.191m, b_P =4.98m);
3) soil parameters (loam, adhesion C_s =30000Pa; internal friction angle φ_s =25⁰).

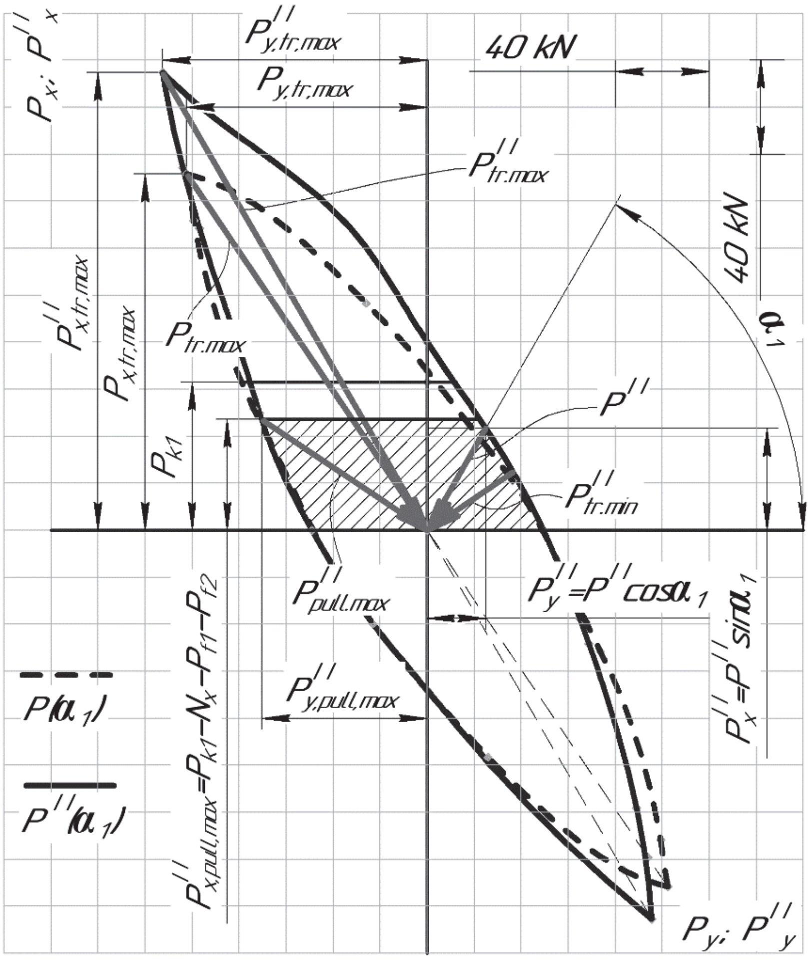

Figure 5: Hodographs of the limit force P, which is applied on the slope board: $P_{tr.max}$, $P''_{tr.max}$– the maximum limit force according to the traction condition, respectively, for P and P''; $P_{x.pull.max}$- maximum limit force, limited by available pull force of bulldozer; $P''_{tr.min}$– the minimum limit force according to the traction condition for P''

With the use of a hodograph, for example $P''(\alpha 1)$, it is possible to determine graphically the value of the limit forces $P_x^{''}$, $P_y^{''}$ taking into account the limitation on the available pull force of the bulldozer. With an increase in the angle α_1

from 0^0 to 120^0, the ratio P'' / P reaches a maximum (at $\alpha_1=0^0$ $P'' / P \approx 1$, at $\alpha_1=120^0$ $P'' / P = 1.34$) and then decreases to a minimum at $\alpha_1=180^0$ (at $\alpha_1=180^0$ $P'' / P \approx 1$). This is due to the fact that the hodograph $P''(\alpha 1)$ takes into account the change in the pressure on the caterpillars. With an increase in the pressure on the caterpillars, the traction force increases. The maximum and minimum values of the limit force applied on the slope board at $0^0 \le \alpha_1 \le 180^0$: $P_{tr.max}(124^0)=182$kN, $P''_{tr.max}(120^0)=225$kN; $P_{tr.min}(34^0)=44$kN, $P''_{tr.min}(34^0)=42$kN. When comparing the available pull force of the bulldozer ($P''_{x.pull.max}$) and the limit force ($P''(90^0)$), it was determined that 60% of the traction force is used (there is reserve in the amount of the traction force), therefore, an increase in the pull force of the bulldozer is possible.

4. CONCLUSION

1. A mathematical model of the process of cutting soil with the additional slope board of the caterpillar bulldozer has been developed, taking into account its angles of capture and tilt, the volume of the soil drawing prism, the regulatory requirements of the basic machine and its course stability, as well as the mechanical properties of the soil surface;
2. For the caterpillar bulldozer with the additional slope board, mathematical dependencies are defined to determine the limit force that can be applied on the additional slope board, taking into account the preservation of the course stability of the base machine;
3. To determine the course stability of the caterpillar bulldozer with the slope board, a hodograph of the limit force applied on the slope board was drawn, with the use of which the components P_x, P_y for the working process were determined in the Mathcad Prime 3.0 program.

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