Research of the Penetration Process of the Frontal Plow

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Abstract. The aim of the study is to study and analyze the process of penetration (deepening) of the frontal plow. Dependencies are obtained for determining the length of the deepening of the serial and frontal plows into the soil. The dynamics of the process of deepening of the frontal plow is analyzed depending on its dynamic characteristics. A differential equation is obtained that characterizes the process of deepening the frontal plow. Theoretical and experimental studies have established that the depth of the frontal plow is significantly affected by the weight of the plow, traction resistance and the relative position of its working bodies. The length of the path of penetration of the frontal plow does not depend on the width of the plow and is 2.0-2.5 m, which is 3-3.5 times less than the path length of a serial plow of equal width.

Keywords: soil, frontal plow, body, coulter, tractor, deepening path, traction resistance, working width, gravity.

1. Introduction

Determining the path of penetration of the plows is of great importance, since flaws at the ends of the field and, accordingly, efficient use of land depend on it. It is known that the deepening of the working bodies of tillage machines, including the plow, mainly occurs under the influence of their own weight. The trajectory of movement in the soil of the working bodies of mounted machines depends on their layout of the working bodies and their parameters, the weight of the machine, soil condition and the hitch pattern. The use of forced penetration into the soil of the working bodies of mounted machines using a hydraulic system is undesirable, since overloads occur in the elements of the implement and tractor [1].

The frontal plow bodies are located on one line perpendicular to the direction of movement. Therefore, it is very important to study the process of deepening the working bodies of the frontal plow
and determine the main factors affecting this process. The aim of the study is to study and analyze the process of deepening of the frontal plow.

2. Research methods

The basic principles and methods of classical mechanics, mathematical analysis and statistics were used in this study.

3. Results and Discussion.

The issues of the path of penetration of the working bodies of tillage machines and deepening were studied by G.N. Sineokov, I.M. Panov [1], P.N. Burchenko [2], A. Tukhtakuziev [3] and Murodov [4]. Stability and the quality of work of the push-pull plows was studied by V. Bulgakov, V. Adamchuk, V. Nadykto and J. Olt [5, 6], the stability of the plow movement was examined by L. V. Gyachev [7], L.B. Dumay and A.N. Migal [8], the interaction of the working bodies of the cultivator and plows for smooth plowing are considered in the works of F. Mamatov, B. Mirzaev, I. Ergashev [9-15] and others.

When working machines with a stepped arrangement of working bodies, the width of the blemish at the ends of the field that occurs when the plow is penetrated into the soil, G.N. Sineokov suggests determining by the following relationship [1]

\[ B = S + L, \]

where \( S \) is the deepening path of the rear working body; \( L \) is the distance between the front and rear working bodies.

Moreover, the depth path of the rear working body of the machine can be determined by the formula [1]

\[ S = \arctg \left( \frac{\varepsilon + \varepsilon_0}{2} \right), \]

where \( \varepsilon \) and \( \varepsilon_0 \) are the clearance angle at the beginning and at the end of the penetration into the soil of the working bodies of the plow, respectively; \( a \) - processing depth.

The working bodies of the frontal plow are located in one row - frontally, so the path of deepening the frontal plow will be equal to [1]

\[ S_F = S = \arctg \left( \frac{\varepsilon + \varepsilon_0}{2} \right). \]

Then, during the operation of the frontal plow, at the ends of the field, flaws remain \( n_f \) times smaller than during the operation of serial plows. The value of \( n_f \) can be determined by the following dependence

\[ n_f = \frac{S}{S_F} = 1 + \frac{L}{\arctg \left( \frac{\varepsilon + \varepsilon_0}{2} \right)}. \]

It can be seen from (2) and (3) that with an increase in the width of the plow, the untreated flaws in serial plows will increase, while in frontal plows it remains unchanged.

For serial plows, the calculated clearance angle \( \varepsilon \) is equal to the angle of inclination of the straight line drawn through the toe of the share and the end of the field board, that is [1]

\[ \varepsilon = \arctg \frac{h}{l}. \]

where \( h \) is the clearance between the bottom of the furrow and the end of the field board; \( l \) is the distance from the toe to the end of the field board.

The standard plow body has \( h \leq 10 \text{ mm} \) and \( l \approx 60 \text{ cm} \), therefore \( \varepsilon = 1^\circ \) [1]. The actual clearance angle \( \varepsilon' \) always exceeds the calculated value \( \varepsilon \) due to the indentation of the end of the field board of the body into the bottom of the furrow with a depth of \( \Delta h \), i.e. [1]

\[ \varepsilon' = \ctg \frac{h + \Delta h}{l}. \]
In the frontal plow, the end of the hull is the end of the wing of the slave, so the actual clearance angle is

$$\varepsilon_f = \operatorname{ctg} \left( \frac{h + \Delta h}{l_f} \right),$$  

(7)

where $l_f$ is the distance from the toe of the body share to the end of the wing.

The distance $l_f = l_1 + l_{kz}$, where $l_1$ is the distance from the toe of the ploughshare of the body to the slave; $l_{kz}$ is the length of the wing of the slave. Then, with the known length of the wing of the coulter and the actual angle of the gap, the height of the wing of the end of the couch is determined from the following relationship

$$h = \left( \frac{L}{\pi} \arctg \frac{a}{b} + l_{kz} \right) \varepsilon_f - \Delta h,$$

(8)

The depth of immersion in the soil of the wing end $\Delta h$ of the front plow $\Delta h$ should be $\Delta h = 0$, since otherwise the plow removes the soil layer of the bottom of the furrow and shifts it towards the hull. This leads to an increase in traction resistance and clogging of the plow with soil.

Given the above, the actual clearance angle for the frontal plow is determined by the following formula

$$\varepsilon_f = \arctg \left( \frac{h}{L \arctg \frac{a}{b} + l_{kz}} \right),$$

(9)

The depth path of the frontal plow is determined

$$S = \arctg \left[ \frac{h}{L \arctg \frac{a}{b} + l_{kz}} \right] + \Delta \varepsilon,$$

(10)

Where $\Delta \varepsilon = (\varepsilon_0 - \varepsilon)/2$.

In addition to kinematic parameters, the plow deepening path depends on the dynamic characteristics of the plow: mass, moment of inertia and the speed of deepening. Therefore, for a complete picture of the depth of the plow, it is necessary to analyze the dynamics of the depth of the process.

When deepening a plow in a longitudinally vertical plane, the plow's gravity force $G = mg$, the soil resistance forces on the hulls ($R_x$ and $R_z$) and the coulters $R_z$, as well as the inertia forces act (Fig. 1). Assume that the traction resistance of the courier is also applied to the main body.

In describing the deepening process, we use the second-order Lagrange equation [16]

$$\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{\varphi}} \right) + \frac{\partial \Pi}{\partial \varphi} = Q_{\varphi},$$

(11)

where $T$ is the kinetic energy of the plow; $\varphi$ is the generalized coordinate; $Q_{\varphi}$ is the generalized force.

As a generalized coordinate, we take the angle of rotation of the plow frame $\varphi$ in the process of deepening. We express the generalized coordinate $\varphi$ in terms of the lifting height of point A — the toe of the body share. We conventionally assume that the soil resistance forces to the hull penetration are applied at point A. For the origin, we take the instant center of rotation of the plow - point $\pi$. The generalized force $Q_{\varphi}$ is defined as the sum of the moments with respect to the instantaneous center of rotation.
Fig. 1. Scheme of forces acting on the frontal plow during deepening: 1 - hitch; 2 - a basic wheel; 3-case; 4 - the stand of the reserve; 5 - courier

The kinetic energy of the system can be determined by the following expression [16]
\[ T = \frac{1}{2} m \nu_\alpha^2 = \frac{1}{2} m l_\alpha^2 \phi^2, \]  
where \( m \) is the mass of the plow; \( \nu_\alpha \) is the relative speed of point A during rotation relative to the instantaneous center of rotation; \( \phi \) - the derivative with respect to the generalized coordinate or the angular velocity of rotation of the plow frame.

Then
\[ \frac{\partial T}{\partial \phi} = m l_\alpha^2 \phi \]  
and
\[ \frac{d}{dt} \left( \frac{\partial T}{\partial \phi} \right) = m l_\alpha^2 \dot{\phi} \]  
(13)

The potential energy of the system is determined according to the expression
\[ \Pi = m g l_\phi \phi. \]

Then
\[ \frac{\partial \Pi}{\partial \phi} = m g l_1 \]  
(14)

The generalized force is defined as the sum of the moments of forces relative to the instantaneous center of rotation
\[ Q_\phi = \sum M_x = -R_x (h_2 + z + l_x \cos \alpha_x) + m g l_1 + R_z (x_p + x_1), \]
where \( R_x, R_z \) - horizontal and vertical component of the resistance forces of the plow; \( L_n \) is the length of the lower link of the tractor.

The values of \( R_x \) and \( R_z \) will change with changing depth of processing. This change is expressed through the generalized coordinate. For this, the processing depth is expressed in terms of \( \phi \). Then \( R_x \) and \( R_z \) are determined
\[ R_x = \delta_x K B_p (x_p + x_1) \sin \phi, \]  
(15)
\[ R_z = \delta_z K B_p (x_p + x_1) \sin \phi, \]  
(16)
where \( \delta_x, \delta_z \) - proportionality coefficients of resistivity and processing depth; \( K \) - soil resistivity; \( B_p \) is the width of the plow; \( x_p, x_1 \) - the longitudinal coordinates of point A.

In view of (15) and (16), the generalized force is determined
\[ Q_{\varphi} = KB_p(x_p + x_i) \sin \phi [\delta_2([x_p + x_i] - \delta_3(h_2 + z + l_n \cos \alpha_n))] + mgl, \]

or
\[ Q_{\varphi} = M \sin \varphi + mgl, \quad (17) \]

Where \( M = KB_p(x_p + x_i)[\delta_2([x_p + x_i] - \delta_3(h_2 + z + l_n \cos \alpha_n))] \).

Substituting the values (12), (14) and (17) into the Lagrange equation (13) we obtain the following differential equation characterizing the process of deepening the frontal plow

\[ ml^2 \ddot{\varphi} - M \sin \varphi = 0 \quad (18) \]

Equation (18) is called an equation without the right-hand side. To solve it, we introduce the notation
\[ \frac{M}{ml^2} = \beta. \]

Then the equation can be written as
\[ \ddot{\varphi} - \beta \sin \varphi = 0 \quad \text{or} \quad \frac{d^2 \varphi}{dt^2} - \beta \sin \varphi = 0. \]

This is an incomplete second-order differential equation [12]. Find a general solution to this equation.

To do this, \( \frac{d\varphi}{dt} = z \), we then assume \( \frac{d}{dt} \left( \frac{d^2 \varphi}{dt^2} \right) - \beta \sin \varphi, \) i.e. where from \( dz = \beta \sin \varphi dt \).

Integrating the obtained expression, we have
\[ \int dz = \int \beta \sin \varphi dt, \quad \text{i.e.} \ z = \frac{t \beta \sin \varphi + C_1}{1}. \]

Consequently
\[ \frac{d\varphi}{dt} = t \beta \sin \varphi + C_1 \quad (19) \]

or
\[ d\varphi = (t \beta \sin \varphi + C_1) dt. \quad (20) \]

We integrate expression (20) and have
\[ \int d\varphi = \int (t \beta \sin \varphi + C_1) dt. \]

From here
\[ \varphi = \frac{t^2}{2} \beta \sin \varphi + C_1 t + C_2. \quad (21) \]

At small angles you can take \( \sin \varphi \approx \varphi \).

Then from here \( \varphi - \frac{t^2}{2} \beta \varphi = C_1 t + C_2, \)
\[ \frac{\varphi}{1 - \frac{t^2}{2} \beta} = \frac{2(C_1 t + C_2)}{2 - t^2 \beta}. \quad (22) \]

Substituting the initial conditions \( \varphi = \varphi_0; \dot{\varphi} = \varphi_0; t = 0 \) in (19) and (21), we determine the integration constants \( C_1 = \varphi_0; C_2 = \varphi_0. \)

Then the general solution of equation (18) will have the form
\[ \varphi = \frac{2(\phi_0 t + \varphi_0)}{2 - t^2 \beta}, \quad (23) \]

The obtained analytical expression (23) allows us to analyze the process of deepening the working bodies of the frontal plow depending on its geometric and dynamic parameters, which will be taken into account when designing the plows of this design.

The solution of equation (23) on a computer and the results of experimental studies showed that the process of deepening the frontal plow consists of three stages (Fig. 2).

The first stage - the lowering stage, proceeds until the point A touches the surface of the field. The process at a constant speed due to the plow's gravity.

The second stage, the stage of the beginning of the deepening, is unstable, since the value of Q\(\varphi \) will be insufficient for stable deepening.

The third stage - the deepening process is oscillatory, but steady, occurs until the support wheels touch the field surface. For the third stage, the value of Q\(\varphi \) will be sufficient to deepen the working bodies.

Fig. 2. The varying of the depth of processing during deepening of the plow

Experimental studies have shown that the depth of the path is significantly affected by the weight of the plow, the resistance and the relative position of the working bodies. The length of the path of penetration of the frontal plow does not depend on the width of the plow and is 2.0-2.5 m, which is 3-3.5 times less than the path length of a serial plow of equal width.

**4. Conclusion**

An analytical expression is obtained that allows one to analyze the process of deepening of the frontal plow depending on its geometric and dynamic parameters. It is established that the length of the path of deepening of the frontal plow is significantly affected by its weight, traction resistance and the relative position of the working bodies. The length of the penetration path of the frontal plow does not depend on the width of the plow and is 2.0-2.5 m.

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