Determination of balanced plow movement for diamond plowing

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Abstract. Wider furrow of the diamond-shaped plow bottom allows the energy-intensive tractor to move with right wheels along it and due to it to shift the line of plow traction to the right, unloads side support and reduces the traction resistance of the plow. Replacing field boards on all plow bottoms with common field board, installed on the last plow bottom, changes the application place of the balancing reaction of the furrow side and its size as a result the plough traction resistance changes. In vertical plane of the projections, this corresponds to displacement of the friction force of field board along the action line. The diamond-shaped plow bottom as a result of other form of the cut slice, the application place of resultant soil pressure moved in the horizontal plane closer to the tip of the ploughshare in comparison with the ordinary plow bottom. The investigated diamond-shaped plow bottom is mounted on the tractor according to the two-point scheme with horizontal projection of the central traction through attachment point of the lower traction to the tractor. When considering the scheme of the plough with similar field boards on all bottoms (production), we will represent it with one field board on the medium plow bottom that facilitates theoretical analysis. Efforts are considered as the stationary random time functions and statistic method based on the theories of stationary random processes are used for studying dynamic objects under their influence.

1. Introduction
More stringent agricultural requirements are imposed on quality indicators during the inversing plowing than to other types of tillage. Non-compliance of the set depth upward may lead to the removal of the infertile soil to the field surface and leads to the yield reduction [1, 2].

2. Problem Statement
During fluctuations of the plow in the horizontal plane the working width changes. According to the agricultural requirements, actual working width should not deviate from constructive more than 10%. The changes of working width upward result in reduction of soil crumbling, increasing of soil combing, deterioration of plant residues. Reduction of actual working width results in decreasing of plowing aggregate productivity. That is why it is important to achieve steady movement of the plough in the horizontal plane.

3. Research Questions
For the description of the diamond-shaped plow motion as the dynamic system, we make up a simple scheme of forces and movements (Figure 1).
Let us assume that the traction line passes through the tip of the middle plow bottom and coincides with the centre trace of plow mass. In the same point (O) disturbing traction resistance is applied (R)
and resistance force to pulling the plow in the furrow ($F_p$) [3].

![Figure 1. The acting forces on the diamond-shaped plow in the horizontal plane](image)

The dynamics of the system with ideal and non-disturbing when moving fully is described by the second-order Lagrange equations [4, 5, 6]:

$$\frac{d}{dt} \left( \frac{\partial T}{\partial q_i} \right) - \frac{\partial T}{\partial \dot{q}_i} = Q_i,$$

where $T$ – kinetic energy of the system;
$q_i$ – generalized coordinate;
$Q_i$ – generalized force.

For the generalized coordinate, we take the angle of plough rotation (skew) ($\varphi$) in the horizontal plane relative to the point of trailer (C).

Let us define the quantities in the equation (1). Kinetic energy of the system:

$$T = \frac{mV_c^2}{2} + \frac{J\phi^2}{2} = \frac{m}{2} \left( V_c^2 + (k + r)^2 \phi^2 \right) + \frac{J\phi^2}{2},$$

where $m$ – mass of the plough;
$V_c$ – point rate C;
$J$ – moment of plow inertia relative to the vertical axis, passing through point C;
$J_o$ – central moment of plow inertia;
$k$ – length of the tractor hitch;
$r$ – geometrical parameter of the plough (Figure. 1).

After conversion we get:
\[
\left( m(k+r)^2 + J \right) \frac{d^2 \varphi}{dt^2} = Q. \tag{3}
\]

More specific one for plough operation is its clockwise rotation. We take this direction as positive meaning of the angle \( \varphi \) and make up the equation of elementary operation:

\[
\delta A = \delta \varphi \cdot \sum M_c \tag{4}
\]

whence

\[
Q = \sum M_c = R \cdot h_R + F_{\varphi} \cdot h_{\varphi} + N \cdot h_N \tag{5}
\]

where \( h_R, h_{\varphi}, h_N \) – shoulders of corresponding forces (Figure 1). Shoulders of forces \((h_R)\) and \((h_N)\) at small movements are not changed and may be defined through geometrical parameters of the plough (Figure 1):

\[
h_R = (k+r) \sin \eta;
\]

\[
h_N = (k+r + i) \frac{\cos(\delta + \varphi - \alpha)}{\cos \alpha}.
\]

Let us define \( h_{\varphi} \):

\[
h_{\varphi} = (k+r) \sin (\varepsilon' + \varphi)
\]

where \( \varepsilon' \) - angle between the direction of the absolute rate of the mass centre and \( \overrightarrow{V}_C \).

In view of small angles \((\varepsilon')\) and \((\varphi)\), for further calculations we take:

\[
\sin \varepsilon' \cong \varepsilon' \quad \sin \varphi \cong \varphi \quad \tan \varepsilon' \cong \varepsilon'
\]

whence

\[
\varepsilon' = \frac{V_x}{V_c} \cdot \frac{V_y}{V_c} \frac{(k+r)}{V_c} \frac{d \varphi}{dt};
\]

\[
h_{\varphi} = (k+r)(\varepsilon' + \varphi) = \frac{(k+r)^2}{V_c} \cdot \frac{d \varphi}{dt} + (k+r) \varphi. \tag{6}
\]

Quantity of furrow side reaction \((N)\) is changed when turning the plough through angle \((\varphi)\) due to angle change \((\delta)\) between the movement direction and the plane of field board:

\[
N = \frac{q \cdot d \cdot \lg h}{2 \cos(\delta + \varphi)} = \frac{q \cdot d \cdot \lg^2 \cdot \sin \delta}{2 \cos(\delta + \varphi)};
\]

\[
\delta = \delta_0 + \varphi + \varepsilon,
\]

where \( \delta_0 \) – design angle of field board arrangement;

\varepsilon - angle between the direction of absolute rate of field board and \( \overrightarrow{V}_C \).

As \((\delta)\) is small and \((\varphi)\) much exceeds \((\delta)\), expression (7) with sufficient degree of accuracy takes the form:

\[
N = \frac{q \cdot d \cdot \lg^2 \cdot \delta}{2 \cos(\delta + \varphi)} = D \cdot \delta \tag{8}
\]

In view of small angles \((\varepsilon)\), we can write:
\[
\frac{d}{dt} \left( \epsilon \cdot \tan \epsilon \cdot \frac{V_{st}}{V_{c}} \cdot \frac{(k + r + i)}{d} \cdot \frac{d\varphi}{dt} \right).
\]

Based on this:

\[
\delta = \delta + \varphi + \frac{d\varphi}{dt} \cdot \frac{k + r + i}{V_{c}}.
\]

Then the expression (8) will take the form:

\[
N = D \left( \frac{d\varphi}{dt} \cdot \frac{k + r + i}{V_{c}} + \varphi + \delta \right).
\]

Let us substitute the found expressions (6) and (9) in the formula (5):

\[
Q = \sum M_c = R \cdot h_\delta + F_{\varphi} \left( \frac{(k + r)^2}{V_{c}} \cdot \frac{d\varphi}{dt} + F_{\varphi} (k + r) \cdot \varphi + D \cdot h_\delta \cdot \frac{d\varphi}{dt} \cdot \frac{k + r + i}{V_{c}} + \right.
\]

\[
+ D \cdot h_\delta \cdot \varphi + D \cdot h_\delta \cdot \sin \delta = \left( F_{\varphi} (k + r)^2 + D \cdot h_\delta \cdot (k + r + i) \right) \cdot \frac{d\varphi}{dt} + 
\]

\[
+ \left( F_{\varphi} (k + r) + D \cdot h_\delta \right) \cdot \varphi + R \cdot h_\delta + D \cdot h_\delta \cdot \sin \delta.
\]

Substituting this expression in the equation (3), we get:

\[
J \frac{d^2\varphi}{dt^2} + A \frac{d\varphi}{dt} + B\varphi = M(t),
\]

where \( J \) – coefficient of plow inertia:

\[
J = J_\circ + m(k + r)^2;
\]

\( A \) – coefficient, taking into account the resistance to change of plough position:

\[
A = \frac{F_{\varphi} (k + r)^2 + D \cdot h_\delta \cdot (k + r + i)}{V_{c}};
\]

\( B \) – coefficient connections stiffness:

\[
B = F_{\varphi} (k + r) + D \cdot h_\delta;
\]

\( M(t) \) – disturbing moment:

\[
M(t) = R \cdot h_\delta - D \cdot h_\delta \cdot \sin \delta.
\]

The expression (11) presents the equation of forced vibrations of the plough with damping under the action of component force \( R(t) \) (15).

Substituting in the expressions (11-15) parameters of production plough scheme, we get the equation of its movement taking into account dynamic properties.

For the definition of damping feature of plough vibrations, we imagine coefficients of resistance, stiffness and disturbing moment as follows:

\[
\frac{d^2\varphi}{dt^2} + 2h \frac{d\varphi}{dt} + \omega^2 \varphi = \frac{M(t)}{J},
\]

where \( h = \frac{A}{2J} \) – constant of damping;

\[
\omega = \sqrt{\frac{B}{J}} \quad \text{natural frequency of the plough.}
\]
4. Purpose of the Study
The purpose is experimental checking of plough operation in different (mentioned above) variants of aggregation. For example, plough vibrations in horizontal plane depend upon ratio (h / $\omega_0$), and is called the coefficient of damping [7, 8].

At $h / \omega_0 < 1$ (low coefficient of resistance in relation to the coefficient of inertia), the plow movement will have the feature of periodical damping vibrations with amplitude and meaning frequency depending upon the coefficient of inertia. At $h / \omega_0 > 1$ (high coefficient of resistance) vibration movement of the plow is done with aperiodic damping and depends little upon the coefficient of inertia, but mainly with function feature $R(t)$.

Substituting necessary parameters of the plough in the expressions (12-14), we get for the experimental diamond-shaped plow with $L = 600$ mm and one field board on the last bottom $h / \omega_0 = 8...10$. And for production scheme with $L = 800$ mm and ordinary bottoms which cut the vertical furrow side $h / \omega_0 = 6...7$. For the production scheme with $L = 800$ mm and diamond-shaped plough bottoms, we leave only the part of furrow side vertical ($d = 50$ mm) $h / \omega_0 = 3...4$.

It’s clear that the coefficients of vibrations damping $h / \omega_0 >> 1$ for both experimental and production schemes, i.e. the characters of their vibrations are defined mainly with the change of $R(t)$.

The results of experiments show that these vibrations do not result in deviations of plowing width by more than acceptable requirements.

5. Research Methods
When considering the scheme of the plough with similar field boards on all bottoms (production), we will represent it with one field board on the medium plow bottom that facilitates theoretical analysis.

Efforts are considered as the stationary random time functions and statistic method based on the theories of stationary random processes and are used for studying dynamic objects under their influence.

6. Findings
The experimental checking of possibility operation of 5-furrow diamond – shaped plow with the distance between the bottoms 600 mm and prolonged field board (500 mm) on the last bottom when the tractor is displaced into the furrow confirmed the productiveness of this plough.

For the possibility of aggregation of 6-furrow diamond-shaped plow with $T\text{150K}$ according to the variant of its motion along the furrow, it is necessary to offset the traction line not by 370 mm, but only by 270 mm [9, 10, 11, 12, 13, 14, 15]. At the same time, the furrow side reaction (N) and required length of field board ($lg$) will be the same as for 5-furrow plow in tractor motion variant along the furrow. It is necessary to offset tractor linkage to the left by 100 mm for the seedbed unity between the trips, which in turn will compensate the tractor turning point from the force ($R_y$). To carry out this variant of aggregation, it is necessary to have the linkage construction on the tractor for the offset of the symmetry axis to the left by the specified value or close to it.

7. Conclusion
1. The experimental diamond-shaped plow with the reduced distance between the bottoms and one field board on the last bottom has great resistance to the position change in the horizontal plane and because of this its vibrations are done with aperiodic damping.
2. The offset of traction line to the right decreases side pressure of the plow (N) and its traction resistance ($P_x$).
3. Reduction of length of plough (distance between the bottoms) results in more intense change of traction resistance from the traction line offset and takeaway of side support to the last plow bottom in less intense change.
4. Theoretical dependences of traction resistance ($P_x$), side pressure (N) and length of field board ($lg$) on the traction line offset (m), which allow one to do the choice of optimal parameters and variants of aggregation of diamond-shaped plow.
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