The design parameters optimization of the oscillating ploughshare mechanism of the root harvester

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Abstract. The problem of optimizing the design parameters of the oscillating ploughshare drive is solved. The purpose of optimization is to ensure the technological process of digging up the soil and harvesting root crops while expanding the speed range of the harvesting machine. The optimization criterion is the torque amplitude on the drive shaft determined from the dynamic drive model. The value of the optimization criterion depends on the parameters of agricultural background and kinematics of the drive mechanism. The load levels and reliability indicators of the optimized and original design of the digging mechanism are investigated.

1. Introduction. Relevance of the problem
Agriculture is the most important industry in any country. In this regard, an important task arises to improve the efficiency of harvesting grown crops, including by reducing the energy expended and increasing the speed of the harvesting machine [1, 2]. The articles of the authors [3, 4] are devoted to improving the quality of soil cultivation with plowshares. Models of the interaction of plowshares with the soil have been built [5, 6]. The interaction with the soil of active working organs of agricultural machines was study [7, 8]. The purpose of the research [9, 10] is to improve the efficiency of agricultural harvesting machines.

The oscillating movement of the plowshares provides cleaning of the blade and active movement of the soil along the plowshare in any condition. The active plowshare is less susceptible to soil and plant residues sticking.

Most of the research of digging mechanisms with an oscillating plowshare devoted to the kinematics of the process and the choice of mechanism parameters that ensured the process of tossing the soil. Issues of optimizing design parameters are usually not associated with an increase in machine speed. The issues of connection of force effects on the drive of the oscillating ploughshare with the conditions of the technological process in the speed range of the machine are not considered [11, 12].

In present work, the force effect on the drive from the oscillating ploughshare [13] is simulated, which allows solving the problems of the dynamics of the drive, both in the linear and nonlinear formulation [14, 15]. The verification of the adequacy of the model of the interaction of the ploughshare with the soil was carried out during field tests using the design of experiments method [16]. The aim of the study was to expand the range of working speeds of the combine while meeting the technological requirements and ensuring the reliability of the main units of the ploughshare drive.
2. Formulation the optimization problem

The digging mechanism with an oscillating ploughshare rigidly connected to the connecting rod and performing a plane-parallel movement with it is considered [15]. The amplitude of the plowshare oscillations is significantly less than the length of the suspensions. The movement of the ploughshare blade is close to reciprocating motion along the oscillation line. The main design parameters of the mechanism: $r$ - value of the eccentricity, $l$ - the length of the connecting rods, $R$ - the length of the suspensions, $L$ - the distance from the suspension attachment axis to the eccentric shaft axis, $\gamma$ - the angle of inclination of the oscillations, it can be defined as the angle corresponding to the average position of the suspension, $\alpha$ - the angle of inclination of the share to the horizontal.

The optimization criterion is the amplitude of the torque loading the drive shaft and determined based on the dynamic model [15].

The value of the optimization criterion is determined by the following factors:

Agrotechnical parameters: mechanical characteristics of the soil layer, coefficient of friction between the soil and the ploughshare, the width of the ploughshare and the root digging depth $H$.

Kinematic parameters: $\omega$ - ploughshare oscillations frequency, $V$ - forward speed of the combine.

Design parameters: $r$ - eccentricity, $\alpha$ - angle of ploughshare installation; $R$ - length of suspensions.

The values of the parameter $L$ are determined by the design of the combine frame, and the variation of the parameter $l$ does not significantly affect the magnitude of the amplitude.

Dynamic parameters: stiffness coefficient $c$, dissipative coefficient $h$, inertial moment $J$. It is advisable to take the dynamic parameters constant and independent of the variable design parameters. This assumption becomes possible due to the smallness of the eccentricity.

Thus, the problem of selecting the design parameters of the oscillating ploughshare mechanism is reduced to choosing the optimal combination of the parameters $r$, $\alpha$, and $R$ for the given basic agrotechnical and dynamic parameters and for a given operating mode.

Constraints were imposed on the variable parameters to ensure the technological mode of digging up the soil layer. The constraints are reduced to the fulfillment of the conditions:

Condition 1. In the cutting phase, the cutting angle $\alpha_c$ must be positive (no friction condition between the lower surface of the ploughshare and the bottom of the furrow)

$$\alpha_c = \alpha - \arctg\left(\frac{V_r \sin \gamma}{V + V_r \cos \gamma}\right) > 0 \quad (1)$$

$V_r$ - relative speed of the ploughshare.

With the specified values of the design parameters and the specified operating frequency of the oscillations $\omega$, condition 1 can be used to determine the lowest operating speed of the combine $V_{\min}$, providing a positive value of the cutting angle $\alpha_c$.

Condition 2. The angle between the vertical and the tangent to the trajectory of the ploughshare when upward motion (tossing phase) must take negative values

$$\varepsilon_{up} = \frac{\pi}{2} - \arctg\left(\frac{V}{V_r \sin \gamma}\right) - \arctg \gamma \leq 0 \quad (2)$$

With the specified values of design parameters and the specified value $\omega$, condition 2 can be used to determine the highest working speed of the combine $V_{\max}$, which ensures the absence of cutting resistance forces in the tossing phase.

Condition 3. The angular velocity $\omega$ must exceed $\omega_{\min}$ - the smallest value that provides tossing of the soil. The smallest value of the angular velocity is determined under the condition that soil separation from the ploughshare occurs at the beginning of the cutting phase.
\[ \omega > \omega_{\text{min}} = \left( \frac{g \cos \alpha \cos \beta}{r \sin (\gamma - \alpha)} \right)^{1/2} \]  

(3)

\( \beta \) - angle between the longitudinal axis of the connecting rod and the line of inclination of oscillations.

At given fixed values of design parameters, condition 3 can be used to select the operation mode of the combine - the value of the operating frequency of the plowshare oscillations, which provides soil tossing.

Conditions 1, 2, 3 determine the area of optimization of design parameters for a given operating mode \( \omega \) and \( V \), or, for specified design parameters allow to determine the optimal operating mode - the frequency of oscillations of the ploughshare \( \omega \), which provides soil tossing, and the speed range of the combine \( V \in [V_{\text{min}}; V_{\text{max}}] \).

Thus, the problem of choosing the optimal parameters of the oscillating ploughshare drive is a problem of multifactorial minimization of a function in the presence of constraints on the parameters that determine the value of this function.

3. Optimization algorithm

Based on the Hook-Jeeves method [17], a program for minimizing the torque amplitude has been developed. The search for the minimum torque amplitude was performed in the zones where conditions (1, 2, 3) are met. Optimization subject to constraints is implemented based on the method of penalty functions [18, 19]. The method involves the formation of a new optimization criterion, including both the initial criterion and the constraints. The new generalized optimization criterion coincides with the original criterion inside the permissible area, and when it goes beyond its boundaries, it sharply increases:

\[ F(x, \tau) = f(x) + \sum_{j=1}^{m} \left[ 0.5 \left( R_j(x) + |R_j(x)| \right) \right]^2 \]  

(4)

\( f(x) \) - the initial optimization criterion,

\( R_j(x) \) - functions of constraints represented by inequalities,

\( \tau > 0 \) - positive coefficient.

If the point \( x \) is inside the valid area, the second term turns to zero, and the generalized optimization criterion coincides with the original criterion. However, when you go beyond the permissible range, the second term becomes a positive number. With the help of the coefficient \( \tau \), its value increases, and the total value of the generalized optimization criterion increases sharply. Thus, after going beyond the boundaries of the admissible area, the optimization algorithm changes the search direction, trying to return inside the constraint area.

The algorithm for choosing the optimal design parameters of the oscillating ploughshare includes the following steps:

1. Input of initial parameters.
2. Checking the fulfillment of conditions (1-3), correction of parameters.
3. Calculation of the moment of resistance forces \( M_r \) based on the model of interaction of the ploughshare with soil [13], finding of torque amplitude \( A_M \) based on the dynamic model of the drive [15]. It is advisable to represent the moment function \( M_r \) as a segment of the Fourier series. The amplitude of the first harmonic of the torque \( M \) can be taken as an optimization criterion \( A_M \).
4. Choice of independent parameters of minimization; entering the boundaries of their change.
5. The procedure for minimizing the function \( A_M \) taking into account constraints (1-3) and the limits of variation of the minimization parameters.
6. Output of results - parameter values and \( A_M \) value.
4. Obtained results

The results of two-parameter optimization on parameters $\alpha$ and $r$ at a fixed value of $R$ and a given operating mode ($\omega$ and $V$) are illustrated in Figures 1, 2.

Figure 1 shows the optimization criteria values using constant-level lines. The boundaries of the optimization area (shaded zone) are determined from conditions (1, 2, 3). Within a valid area, the optimization criterion function is smooth, without local extremes. The absolute minimum hits the point $(\alpha_{opt}; r_{opt})$. In the case of optimization for the parameter $\alpha$ with a fixed value of the parameter $r$, the value $\alpha_{opt}$ falls at a point lying on the boundary I $\alpha_c = 0$. In the case of optimization for the parameter $r$, with a fixed value of the parameter $\alpha$, the value $\alpha_{opt}$ falls at a point lying on boundary III $\varepsilon_{up} = 0$, or on boundary II $\omega = \omega_{min}$.

Figure 2 shows the areas of two-parameter optimization by $\alpha$ and $r$ for various operating modes. The root harvester, having a fixed oscillation frequency of the ploughshare, must provide the process of digging up the soil layer in a certain range of operating speeds. In this case, the areas of allowable values $\alpha$ and $r$ have a common boundary III, determined by the condition $\omega = \omega_{min}$ and independent of the speed of the combine. However, optimal values $(\alpha_{opt}; r_{opt})$ for the speed range give an increase in the value of the optimization criterion.

The behavior of the optimization criterion $A_m$, determined for the optimal values $(\alpha_{opt}; r_{opt})$ corresponding to different values of the parameter $R$, is shown in Figure 3. Each operating mode $(\omega, V)$ corresponds to the lowest value of $R$, at which it is possible to fulfill the conditions that provide a favorable mode of digging the soil layer. The values of $R$ belonging to the shaded area $R_{opt}$ are suggested as optimal for a fixed oscillation frequency of the ploughshare and a given range of operating speeds $V$. Thus, when the combine is operating at a frequency $\omega = 45s^{-1}$ and the operating speed $V$ changes from 0.5 to 1.5 m/s, the optimal values of $R$ correspond to the interval $[16; 19]$ centimeters.

![Figure 1. The area of two-parameter optimization for the ploughshare angle $\alpha$ and eccentricity $r$, lines of equal level of the optimization criterion are indicated $A_M (H \cdot m)$.](image1)

![Figure 2. Two-parameter optimization in terms of the ploughshare angle $\alpha$ and eccentricity $r$ for specified range of operating speeds of the combine $V \in [0.5; 1.5] (m/s)$.](image2)
Figure 3. Optimum values of the plowshare suspension length (R_{opt} zone) for various operating modes

When choosing the optimal parameters (r, α, R) for a narrow speed range (ΔV = 0.5 m/s), it is possible to reduce the torque amplitude in comparison with the calculated values for the actual parameters of the root harvester. With the expansion of the range of machine speeds, an increase in the level of dynamic loads is observed, and the calculated values of the torque amplitude of the optimized structure exceed the calculated amplitude values for the initial design parameters. However, for the latter, conditions (1, 2, 3) are not met and, therefore, there are additional resistance forces not taken into account in the mathematical model. The calculated values of the moment amplitudes for the initial parameters (r, α, R), are shown by curve I (non-optimized design) in Figure 4. The dashed sections of curve 1 correspond to the areas where the fulfillment of conditions (1, 2, 3) is violated.

Figure 4. Optimized drive shaft torque amplitudes A_{M} at different frequency of vibrations of the ploughshare (a - ω = 45 s^{-1}, b - ω = 55 s^{-1})
The results of optimization by parameters \((r, \alpha, R)\), for various operating modes \((\omega, V)\) are presented in Table 1.

**Table 1. Optimization results of design parameters for various operating modes**

| The operating mode | Optimal parameter values |
|---------------------|--------------------------|
| \(\omega, \text{s}^{-1}\) | \(V, \text{m/s}\) | \(r, \text{cm}\) | \(\alpha, \text{rad}\) | \(R, \text{cm}\) |
| 45 | 0.5-1.0 | 2.1 | 0.27 | 18 |
| 45 | 1.0-1.5 | 3.3 | 0.26 | 18 |
| 55 | 0.5-1.0 | 1.8 | 0.26 | 19 |
| 55 | 1.0-1.5 | 2.6 | 0.24 | 19 |
| 55 | 0.5-1.5 | 3.5 | 0.23 | 19 |
| 55 | 1.0-2.0 | 3.5 | 0.29 | 19 |

5. **Conclusions**
Solving the optimization problem for a given mode \((\omega, V)\) can provide a significant reduction in the level of dynamic loads in the drive shafts. With the expansion of the speed range of the machine, the dynamic loads of the drive shafts increase. To operate the harvester at speeds up to 2.5 m/s, it is required to increase the length of the plowshare suspensions to \(R = 21 \div 22\ \text{cm}\), and the oscillation frequency of the plowshare to \(\omega = 60 \div 65\ \text{s}^{-1}\). In this case, dynamic loads increase, but the fatigue safety factors of the main drive units remain within the limits of norm [20].

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