Justification of parameters of a four-row disk harrow using the experiment planning method

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Abstract. Disk harrows with individual installation of the disk on a separate stand are widely used in resource-saving technology of soil preparation for grain crops after late harvesting of row crops (corn, sunflower). Four-row disc harrows provide soil preparation for grain crops in one or two passes through the maize and sunflower predecessors. The main parameter of the disk harrow is the depth of processing, the value of which depends on the disk setting angle to the unit movement direction. An increase in the setting angle is accompanied by not only an increase in the depth of processing, but also the traction resistance and fuel costs for soil treatment increase. However, a number of disk parameters also affect the processing depth value – the diameter, the inclination angle of the disk in the vertical plane, the width of the chamfer cutting edge, the vertical load on the disk, the thickness of the disk and a number of others. Consideration of these factors during the adjustment to the required processing depth will reduce the disk setting angle to the direction of the unit movement, which will help to reduce disk harrow traction resistance and increase the fuel efficiency of preparing the soil for sowing grain on rowed predecessors.

1. Introduction
Disk harrows with spherical disks installed on an individual axis are widely used in resource-saving technologies of soil preparation [12,3,4,7-10], for sowing grain crops after late-harvested macropodal tilled crops [11]. For one pass of a four-row disk harrow, the soil is completely prepared for sowing according to these predecessors. The disk harrow processing depth [13] is changed by adjusting the disk setting angle to the direction of movement. The spherical disk setting angle increase is accompanied by a proportional increase in traction resistance and energy consumption for processing, which will lead to a higher fuel consumption of the disk harrow commensurate with a moldboard plowing. This circumstance will not ensure the feasibility of soil cultivating by a four-row disk harrow for sowing grain after tilled crops. This problem is particularly relevant for disk harrows with a large width and the number of parallel rows equals four. Processing depth of the disc harrow [14], as we know, depends not only on the setting angle of the spherical disk, but also on its parameters, which are not taken into account during the approach angle adjustment. The disk parameters that affect the processing depth include its diameter and thickness, the vertical load and the disk inclination angle in the vertical plane, the speed of particles escaping from the inner surface of the sphere, and a number of others. Therefore, in order to reduce the disk traction resistance, depending on the processing depth, it is necessary to optimize the value of the setting angle for certain and actual parameters of the disk by
considering all factors. Optimization of the disk setting angle and the parameters of the disk harrow for a fixed value of the processing depth will make it possible to reduce the traction resistance and increase the fuel efficiency of soil preparation for grain crops [11] for macropodal tilled predecessors.

2. Materials and methods

Optimization of disk harrow parameters is performed by the method of planning a multi-factor experiment. A mass-produced four-row disc harrow of the “BDM-3,2x4” brand with the “HTZ-150K” tractor has been selected as the object of the research. The traction resistance of the disc harrow has been measured by a TKZ-25 dial dynamometer. The disk inclination angle in the vertical plane and the angle of inclination to the direction of unit movement has been measured by the “Pro-Digit MICRO” digital inclinometer. The permissible measurement error of the device did not exceed 0.20. The movement speed has been determined by the standard dashboard speedometer and has been specified by the time of passing a fixed distance. It has been planned to conduct a three-factor experiment in three-fold replication.

Factors and variability intervals are shown in table 1.

Table 1. Factors and levels of their variation

| Factor title                              | Coded designation | The variability interval | Levels of factor variation |
|-------------------------------------------|-------------------|--------------------------|----------------------------|
| The disk inclination angle in the vertical plane, deg. | X₁                | 7                        | 14                         | 7 | 0 |
| The angle between the axis of the disk and the direction of movement (approach angle), deg. | X₂                | 5                        | 25                         | 20 | 15 |
| Recommended speed of movement, km/h.      | X₃                | 2                        | 12                         | 10 | 8 |

The matrix of a three-factor experiment has been selected [2,5]. To exclude the accidental influence of additional factors on the optimization parameter, randomization has been performed according to the table of random numbers. A factor experiment has been implemented and the values of the response function in replications have been determined. The homogeneity of variances in replications has been checked by the Cochran criterion. It has been found that at a given level of significance, the homogeneity of variances in parallel experiments has not been rejected. The values of the coefficients of the regression equation have been determined by using the least square method, using known dependencies [1]. The significance of the obtained coefficients of the regression equation has been evaluated using the Student criterion [6]. It has been established that all coefficients of the regression equation are significant. The resulting regression equation has the form:

\[ y_k = 6.456 + 0.0171x_1 + 0.023x_2 - 0.175x_3 - 0.0001x_1x_2 - 0.0005x_1x_3 - 0.0025x_2x_3 - 0.0007x_1^2 - 0.0047x_2^2 + 0.0113x_3^2, \]

where \( y_k \) – the coded value response function;
\( x_1 \) – the coded value of the spherical disk setting angle to a vertical plane of the unit;
\( x_2 \) – the coded value of the disc setting angle to the direction of the unit movement;
\( x_3 \) – the coded value of the recommended speed.

Analysis of the mathematical model equation allows determining the degree of influence of each factor on the optimization parameter, which is set by the absolute value of the regression coefficient. The equation shows that the factor \( x_2 \) has the greatest influence on the optimization parameter, and factor \( x_3 \) has the least influence. The free term of the equation represents the average value of the response function.
The equation with the coded value of the factor has been translated into natural ones by using the ratio:

\[ X_1 = 7x_1 + 7, \quad X_2 = 5x_2 + 20, \quad X_3 = 2x_3 + 10, \]

where \( X_1 \) – the natural value of the disk inclination angle in the vertical plane, deg;
\( X_2 \) – the natural value of the disk setting angle to the direction of the unit movement, deg;
\( X_3 \) – the natural value of the unit operating speed, km/h.

3. Results and discussion

The regression equation must accurately describe the process being researched. The test for the ability of the mathematical model to accurately describe the process under study has been carried out using the Fisher's ratio test. It has been found that with a probability of 95%, the obtained regression equation reliably describes the obtained experimental dependence.

In the regression equation, all factors have a dimensionless value. For this reason, it is not possible to set the values of factors at which the response function takes the minimum value in our case. The resulting regression equation in the implementation of the experiment plan, for subsequent analysis, must be converted to the canonical form by a well-known method [6].

After converting the equation to the canonical form, it is studied for the extremum. It is known that the function reaches an extremum at the point where the first derivative meets the requirements:

\[
\frac{dy}{dx_1} = 0 \\
\frac{dy}{dx_2} = 0 \\
\frac{dy}{dx_3} = 0
\]  

(2)

By differentiating equation (1) for each of the variables and equating the first derivatives of function to zero, a system of equations has been obtained:

\[
\frac{dy}{dx_1} = 0.0171 - 0.0001x_1 - 0.0005x_2 - 0.0014x_3 \]
\[
\frac{dy}{dx_2} = 0.203 - 0.0001x_1 - 0.0025x_2 - 0.0094x_3 \]
\[
\frac{dy}{dx_3} = -0.175 - 0.0005x_1 - 0.0025x_2 + 0.0226x_3
\]  

(3)

Solving a system of differential equations, the coordinates of the point at which the function reaches its maximum value: \( B_1 = 0.021, B_2 = -0.0535, B_3 = 0.0098 \) are determined. The response value at the new origin of coordinates was \( Y_s = 7.55 \).

The canonical equation of a mathematical model with the natural value of factors takes the form:

\[ Y - Y_s = B_1X_1^2 + B_2X_2^2 + B_3X_3^2 \]
\[ Y - 7.55 = 0.021X_1^2 + 0.0535X_2^2 + 0.0098X_3^2. \]  

(4)

Having obtained the canonical equation, its research is carried out for the extremum. By equating the response value to a certain constant value, equal output curves are obtained.

It follows from the expression 4 that the coefficients for the disk setting angle to the direction of movement \( \alpha \) and the disk inclination angle in the vertical plane \( \beta \) have different signs. This suggests that the response function, with a fixed speed, has the shape of an elliptic paraboloid. The maximum value of the function is reached at the point with coordinates - the disk setting angle to the direction of movement \( 17.86^0 \) and the disk inclination angle in the vertical plane \( \beta = 6.36^0 \). The optimal speed value is \( \upsilon = 9.41 \text{ km/h} \). The minimum value of the specific traction resistance of a disk harrow is determined to be 7.55kN/m at the optimal value of factors. The traction resistance of the disk harrow was 24.19 kN with a working width of 3.2 m and a processing depth of 0.12 cm.
Comparative tests of a mass-produced four-row disk harrow of the BDM-3.2х4 with the HTZ-150K tractor have been carried out. Drawbar tests have been carried out in a proper field area by using a traction dynamometer in a three-fold replication. According to the test results, the average value of traction resistance was 27.84 kN, the specific traction resistance was 8.7 kN/m, the operation speed was 9.1 km/h, and the processing depth was 0.12 m.

4. Conclusions
- The amount of traction resistance is significantly affected by the disk inclination angle in the vertical plane, the disk-setting angle to the direction of the unit movement and the operation speed.
- The optimal parameters of factors affecting the traction resistance of the disk harrow BDM-3.2х4 have been determined. The maximum value of the disk setting angle to the direction of movement should be 17.86°, the maximum value of the disk inclination angle in the vertical plane is 6.36°, the maximum speed of the unit is 9.41 km/h. The specific traction resistance of the disk harrow was 7.55 kN/m with maximum parameters and the processing depth of 0.12 m.
- Setting the disc harrow: the tilt angle in the vertical plane 0°, the installation angle of the disc to the direction of movement of the unit 200°, the working speed of 9.0 km/h, tractive resistance four-row disc harrows BDM-3.2х4 has made 27.84 kN for the depth of 0.12 m.

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