https://doi.org/10.17221/87/2017-RAE

Substantiation of the parameters of the disk-knife working body and the study of its work

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Abstract

Kukharets S., Golub G., Biletskii V., Medvedskiy O. (2017): Substantiation of the parameters of the disk-knife working body and the study of its work. Res. Agr. Eng., 64: 195–201.

The work is devoted to the issue of improving the quality of cultivating of root-bearing soil layer and optimizing its agrotechnological properties. Improving the quality of cultivation is due to the application of soil cultivating tools equipped with disk-knife working bodies. They are provided theoretical and experimental study of the work of the disk-knife working body, and it is substantiated its rational parameters. The basis of the substantiation of the parameters of the cultivating tool is the original analytical model, which reflects the process of interaction of the working body with the soil. To study the performance of the process, on the basis of kinematic equations of motion of the individual points of the working bodies, it is developed the analytical model of the motion of the battery of the working bodies. On the basis of the provided analytical researches, they were determined geometrical parameters and developed experimental samples of the disk-knife working body. It was carried out a comparative test in the field of tools equipped with disk-knife working bodies and with standard spherical cut-off discs, which confirmed the effectiveness of the use of disk-knife working bodies. The use of disk-knife working bodies ensures: the burying of plant remains and fertilizers into the root-bearing soil layer, improving the quality of soil cultivation, preserving of its structure, reducing the traction resistance of the body.

Keywords: modeling; field test; twist angle; burying factor; approach angle; tillage depth; traction resistance

In the system of basic and pre-sowing soil treatments, it became widespread soil treatment with tools with disk working tools. Their use reduces soil preparation time (Rusu 2014; Damanauskas, Janulevičius 2015, Hamzei, Seyyedi 2016). It is appropriate to use disk soil tillage tools and in systems of the hill soil tillage (Tarverdyan, Tonapetyan 2016). The use of disk cultivation can reduce the negative impact of crop predecessors on the main culture (Ercoli et al. 2017). The use of disk soil cultivation can reduce carbon dioxide emissions into the atmosphere (Šima et al. 2013; Lu, Liao 2016).

However, due to their structural features, the tillage tools equipped with serial working bodies do not fully provide agrotechnical requirements for the burying of fertilizers, plant residues, herbicides, weed seeds, etc. (Raiesi, Kabiri 2016; Pires et al. 2017). The use of disk cultivation leads to the partial destruction of valuable structural soil conglomerates (Andruschkewitsch et al. 2014; Rücknagel et al. 2017). Disturbance of soil leads to a decrease in its microbiological activity. (Kabiri at al. 2016). When burying organic fertilizers with a disk harrow, some of the fertilizer remains are left on the sur-

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face, which greatly reduces the efficiency of their use (Colbach at al. 2014; Scherner at al 2016). The tillage with serial disk tools does not provide an adequate degree of organic waste burying, which reduces the efficiency of their decomposition (Schneider at al. 2006; Brennan et al. 2014; Sizmur at al 2017).

The results of the performed analysis of existing designs of disk working bodies indicate the promise of their use. However, existing types of designs of disk tillage tools cannot fully ensure the burying of organic residues and organic fertilizers and partially disturb the soil. In addition, they do not provide a rational distribution for the depth of cultivation of plant residues and fertilizers. Therefore, it is necessary to develop a design of a disk working body that would provide the necessary quality indicators for burying into the soil at the optimum depth of stubble, straw, organic and mineral fertilizers with preservation of the soil structure.

MATERIAL AND METHODS

Computer simulation. To study the performance of the process, on the basis of the kinematic equations of motion of the individual points of the working bodies, it was created the analytical model of the movement of the battery of the working bodies (Fig. 1), which was described by a system of equations:

$$\left.\begin{aligned} x_i &= \upsilon_n t + a\cos\beta\cos(\omega t - \alpha) + b\sin\beta + nl\sin\beta \\ y_i &= b\cos\beta - a\sin\beta\cos(\omega t - \alpha) + nl\cos\beta \\ z_i &= -a\sin(\omega t - \alpha) \end{aligned}\right\} \quad (1)$$

where: x_i, y_i, z_i – coordinates of the studied characteristic points A, B, C, D, E, F, A', B' of the model of the working body (m); u_n – velocity of the translational motion of the working body (m/s); *b* – approach angle of the working body (°); *wt* – rotation angle of the working body, deducted from the OX axis in a clockwise direction (°); *l* – the distance between the working bodies in the battery (m); *a*, *b*, – parameters that determine the linear coordinates of the location of the characteristic points of the knife of the working body (m); α – a parameter that defines the angular coordinates of the location of characteristic points (°); *n* – serial number of disks in the battery (*n* = 0,1,2...)

Field studies. To determine the burying factor, they were taken pictures of the field surface. The received photos were processed on a computer by the method of numerical analysis of visual information. Visual information was converted into a numerical array on the basis of intensity and colour. The described numerical array after the corresponding statistical processing and generalization of the information on the surface of the field served to determine the index of burying completeness, as the ratio of the surface area with full burying of the upper layer to the entire area of the treated surface.

The parameters of the quality of soil cultivation (agricultural background – fall-plowing) were determined in two ways: basic (the cultivation was performed with standard spherical cut-off discs of the "European" type installed on a disk harrow with a width of 1.8 m), the proposed (the cultivation was carried out with disk-knife working bodies mounted on a disk harrow with a width of 1.8 m, Fig. 2).

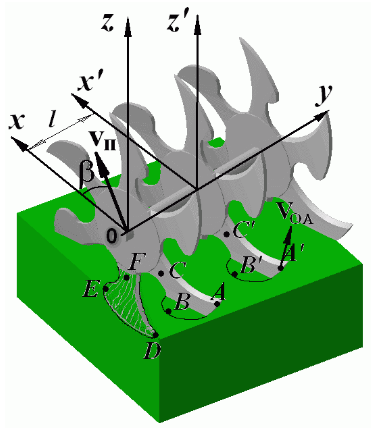

Fig. 1. Graphic presentation of the model of the battery of working bodies
A, B, C, D, E, F, A', B' – characteristic points of the knives of working bodies; V_n – direction of movement of the unit

Fig. 2. General view of the unit as part of the PMZ-6AL and the disk harrow BDN-1.8-RL-1, equipped with disk-knife working bodies

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Determination of traction resistance was carried out by the method of strain gauging in the ground channel. In this case, it was fixed the horizontal component (Px, H) of the resistance forces depending on the approach angle β (°) and the depth of soil cultivation h (m). The value of the traction resistance was determined using a strain-gauge station, with the signal from the electric dynamographs on the two channels being received on the registration device.

Indicator of distribution of plant residues for the depth of cultivation k_r was determined by the formula:

$$k_r = \frac{M_{5...20}}{M_n} \tag{2}$$

where: M_n – mass of plant residues, artificially distributed on the surface of the field prior to the tillage tool (kg); $M_{5...20}$ – the mass of plant residues in the layer of soil 5–20 cm after tillage with the tool (kg)

Distribution of plant remains in the soil layers 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm, was determined by laundering of the soil monolith with the area of 0.1 m^2, of the corresponding thickness, through sieves with a diameter of the holes of 3.1 mm and 0.25 mm.

RESULTS

The aim of the presented work is to improve the quality of cultivating of the root-bearing layer of soil by using disk-knife working bodies. To do this, it is necessary to substantiate the process of work and structural and technological parameters, to experimentally determine the influence of the parameters of disk-knife working bodies on the quality of soil cultivation and to perform comparative studies of the proposed working body with serial working bodies.

Theoretical determination of geometric parameters of a disk-knife working body

The basis of the substantiation is the analytical model (Kukharets et al., 2002; Kukharets et al. 2006), which reflects the process of interaction of the working body with the soil. It is determined, taking into account the complete stress tensor at the top of the crack, the general equations of the working surface (in the conditions of an unblocked or semi-blocked cutting) with a clean detachment Eq. (3) and a pure shear Eq. (4):

$$\cos\frac{\theta_1}{2}\left(1-\sin\frac{\theta_1}{2}\sin\frac{3}{2}\theta_1\right)x'^2+\cos\frac{\theta_1}{2}\left(1+\sin\frac{\theta_1}{2}\sin\frac{3}{2}\theta_1\right)y'^2+ \\ +2\sin\frac{\theta_1}{2}\cos\frac{\theta_1}{2}\cos\frac{3}{2}\theta_1 x'y'=0 \tag{3}$$

$$z' = tg\frac{\theta_2}{2}x' \tag{4}$$

where: θ_1, θ_2 – parameters of the working surface, depending on the physical characteristics of soils (°); x', y', z' – current coordinates of the working surface (m)

As a result of the joint solution of Eqs (3) and (4), it was established the dependence of the shape of the front working surface of the disk-knife soil treating working body on the depth of soil cultivation. The resulting form of the working surface describes the surface of the hyperbolic paraboloid (Fig. 3):

$$x = \frac{H_{max} \times z}{tg\gamma_0 \times y} \tag{5}$$

where: H_{max} – max. depth of soil cultivation with the working body (0.12–0.20 m); γ_0 – the twist angle of the working surface of the knife, towards the rotor's plane of rotation (°); x, y, z – coordinates of the working surface (m)

It was found the dependence of the twist angle γ_0 of the working surface of the knife on the depth of cultivation:

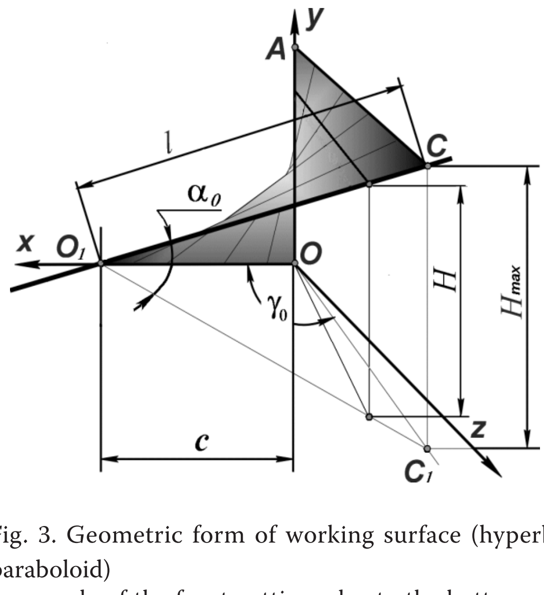

Fig. 3. Geometric form of working surface (hyperbolic paraboloid)
α_0 – angle of the front cutting edge to the bottom of the furrow; γ_0 – the twist angle of the working surface of the knife towards the rotor's plane of rotation

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$$\gamma_0 = \gamma_{\max} - H_{\max}\frac{d\gamma_0}{dH} \quad (6)$$

where: γ_{max} – max. twist angle of the working surface, for a specific type of soil (7–28°); $d\gamma_0/dH$ – an indicator taking into account the mechanical characteristics of the soil environment (16–19°·m^{-1})

The number of (n = 6) knives on one working body (Fig. 4) is defined as:

$$n \le \frac{2\pi r_r}{s + (c\cos\gamma_0)} \quad (7)$$

where: r_r – the radius of the working body, along with the knives installed on it (m); s – projection of distance k between the nearest points of adjacent knives to the plane parallel to the rotor's plane of rotation (m); c – the length of knife (m)

They are defined basic geometrical parameters of the working surface of a knife (Fig. 5).

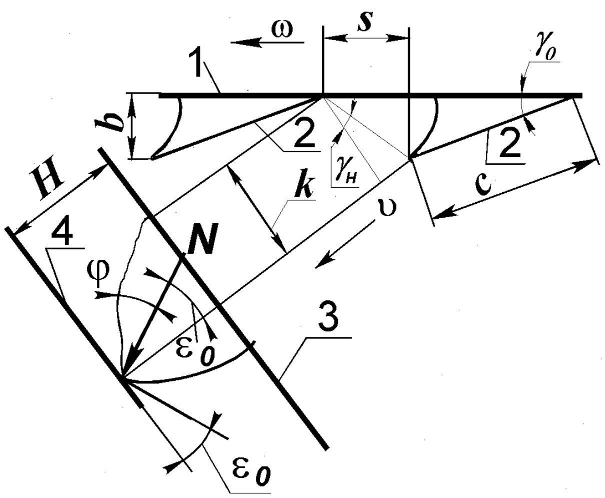

Fig. 4. Scheme to determine the number of knives on the disk and the distance between neighboring knives

1 – horizontal projection of the plane of rotation of the working body; 2 – horizontal projections of the upper edge of the knives; 3 – field surface; 4 – furrow sole; b – projection of the operating width of the working body to the plane perpendicular to the rotor's plane of rotation; k – the distance between the nearest points of the adjacent knives; γ_H – the twist angle of the working surface of the knife to the plane of rotation of the working body, at the nominal depth of cultivation; ϕ – the angle of friction on the surface of the working body, ε_0 – the angle of the bottom edge of the knife to the furrow sole; ω – direction of rotation of the working body; υ – direction of linear movement of soil treating tools

On the basis of the analytical studies they were determined geometric parameters and developed experimental samples of the disk-knife working body (Fig. 6).

Computer modeling of the work of the disk-knife working body

The analysis of the results of experiments on the influence of the structural parameters of knives (length c (mm) and the twist angle γ_0 (°) of the working surface) on the coefficient of burying k_z, allowed to obtain the following equation:

$$k_z = -89.278 + 2.027c + 9.984\gamma_0 - 2.2\times10^{-2}\times c^2 - \\ -7\times10^{-3}\times c\gamma_0 + 1,86\times10^{-1}\times\gamma_0^2 \quad (8)$$

Its research on the extremum allowed (with a determination level of 98.7%) to finally establish the length of the working surface c, which, taking into account the scale factor μ = 5, is 175 mm and the twist angle of the anterior working surface γ_0 = 24°. When these parameters are met, the max. index of k_z is set at 85%.

The analysis of the results of modeling of the influence of the approach angle β (°) of the battery of the working bodies and the distance l between the working bodies in the battery on the height of the butt h_r (m) of the furrow sole allowed obtaining the following equation:

$$h_z = -0.141 - 2.7\times10^{-2}\times\beta + 5.731\times l + \\ +2\times10^{-3}\times\beta^2 - 3.5\times10^{-2}\times\beta\times l + 9.434\times l^2 \quad (9)$$

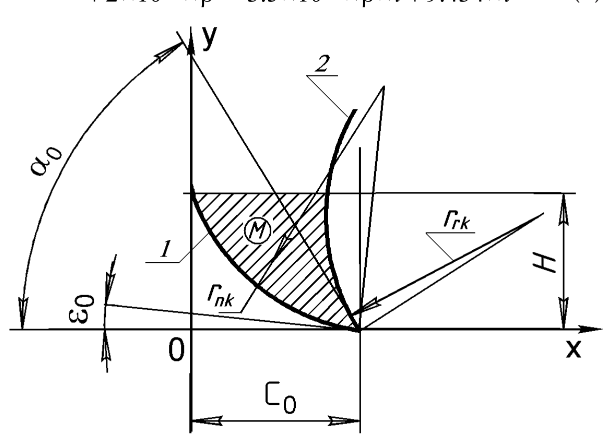

Fig. 5. Theoretical profile of the working part (M) of the knife

1 – lower edge; 2 – upper cutting edge; r_{rk} – radius of the upper cutting edge; r_{nk} – radius of the bottom edge; c_0 – projection of knife length; H – depth of cultivation

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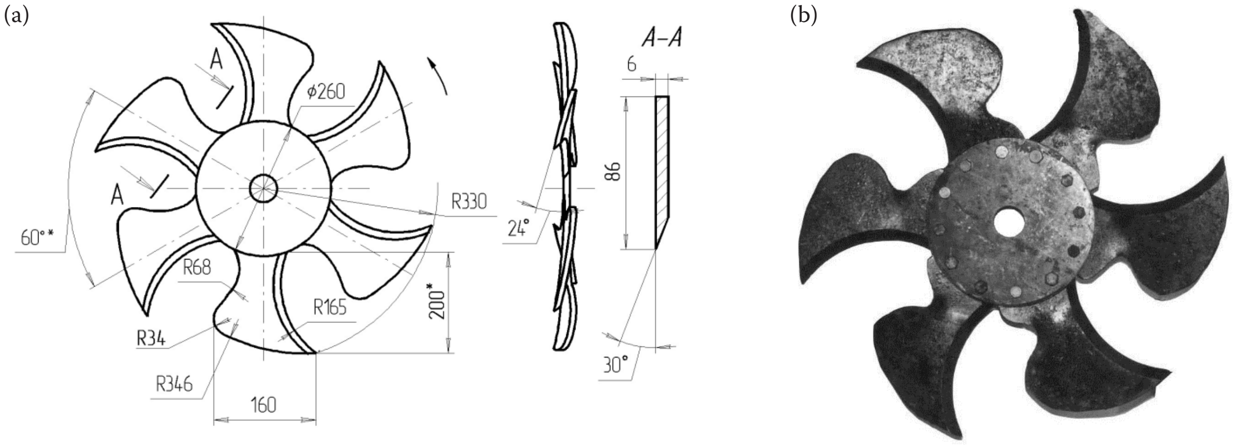

Fig. 6. Disc-knife working body: (a) geometric parameters, (b) general view of the prototype

Its research on the extremum allowed to determine the optimal values of the approach angle of the battery of the working bodies β 20–24° (β_{opt} = 20°) and the distances between the working bodies in the battery 0.18–0.218 m. (l_{opt} = 0.2 m).

Experimental studies of the work of the disk-knife working body

According to the results of experimental studies, the traction resistance of the disk-knife working body is lower on average by 21.6–3.1% of the traction resistance of the spherical cut-out working body and depends on the angle of installation of the working bodies β 18–24° (Fig. 6) and the depth of soil cultivation *h* 0.12–0.2 m. Herewith, the confidence level of the results of the experiment estimated on the student's criterion is 97%.

The analysis of the results of the dependence of the traction resistance *P* (N) on the approach angle β (°) and the depth of cultivation *h* (m) allowed obtaining the following equation:

$$P = 616.518 + 4,538\beta - 84,197h + 0,694\beta^2 - \\ - 0.856 \times \beta \times h + 3.669h^2 \quad (10)$$

On the basis of the conducted experimental research, it was concluded that due to reduction of the contact area with the soil and due to the conoid shape of the working surface of the knife, the proposed design of the working body allows to reduce the size of the traction resistance by 15.7% with the optimal value of the approach angle β = 20° and the depth of cultivation *h* = 0.12 m.

According to the experimental data, it was determined an indicator of the distribution of k_r plant residues according to the depth for the disk-knife working organ, which, depending on the approach angle β, can be described by the polynomial of the 3rd degree (with the determination coefficient R^2= 0.99):

$$k_r = -2,333\beta^3 + 15\beta^2 - 22.667\beta + 72 \quad (11)$$

Reducing of the approach angle β < 20° leads to the appearance of untreated areas of the field, and with an increase in the approach angle it is observed a decrease in the efficiency of distribution of plant remains due to the deterioration of the rotating ability of the disk-knife working organ. The max. dispersion rate for a disk-knife working body is reached at an approach angle β = 20°, and is 76%, which is by 15% more than for spherical cut-out discs.

DISCUSSION

Using of disc-knife working body causes a decrease of energy consumption and labor costs by 20–25% when compared to other types of tillage machines (Rusu 2014; Ahmadi 2016).

Disc-knife working body soil tillage tools have lower specific traction resistance in comparison with other implements for basic soil cultivation (Kogut et al. 2016).

Disc-knife working body fully provides agrotechnical requirements for the burying of fertilizers, plant residues, herbicides, weed seeds, etc in comparison with existing tillage implements and that allows to improve soil quality indicators (Raiesi, Kabiri 2016; Pires et al. 2017).

According to the results of the study of the structural and aggregate soil composition, it was

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established that the number of soil aggregates (d < 0.25 mm and d > 10 mm) which did not meet the agrotechnical requirements from the point of view of erosion stability using disk-knife working bodies decreased by 28.1% to the background The index of burying in comparison with spherical-cut discs has increased by 1.14 times.

Absolute weight moisture of soil in a layer 0–20 cm, when cultivating with disk-knife working tools, in comparison with spherical-cut discs was higher by 5.9% and corresponded to agrotechnical requirements. The bulk density of the soil cultivated with implements with disk-knife working bodies corresponded to the agronomic requirements and was 1.20 g·cm^{-3}, which is by 6.2% less than for the variant with spherical-cutting discs and by 36.8% less when compared to the agricultural background. It was established that during the cultivation with disk-knife working tools the value of the resistance of the soil hardening is minimal and is 49.8 kPa, which is less by 15.7% when compared to the treatment with spherical cut-off discs and by 43.0% less when compared to the background. The volume bearing ratio while using disk-knife working bodies was by 51.4% smaller when compared to the background and corresponded to a standard value for a plowed field.

The analysis of the obtained from the production inspection results on the quality of soil cultivation suggests a positive effect on the structural and agrotechnological state of the soil treated with the disk-knife working body when compared to treatment with the spherical cut-out discs (Šima et al. 2013; Ahmadi 2016).

Further research is planed to be conducted not only with passive disk-knife working tools but with active ones as well.

CONCLUSION

The main structural parameters of the working surface of the knife of the working body are: geometric form – straight conoid (hyperbolic paraboloid); height (corresponds to max. depth) h 0.2 m; moldboard length c 0.175 m; twist angle of the generatric γ_0 24°; radius of the front cutting edge r_{rk} 0.165 m; radius of the bottom edge r_{nk} 0.346 m; the shape of the rear edge is described by the part of the ellipse with radii of curvature a_e 0.1 m and b_e 0.06 m. Number of knives n was 6. The range of optimal values of the angle of attack of the battery of the disk-knife working bodies is defined within β 20–4°; the distance between the working bodies in the battery is l = 0.18–0.218 m. The zone of the optimum values of the speed of the machine-tractor unit varies u_n = 3–0 km·h^{-1}.

Application of soil tillage tools with disk-knife working bodies allows reducing the number of erosion-dangerous aggregates of soil by 28.1% when compared to agricultural background and by 7.0% when compared to the use of spherical cut-out discs; the coefficient of structurality when compared to spherical cut-out discs increased by 12.9%. The index of burying of fertilizers and plant residues in comparison with spherical cut-out discs increased by 1.14 times and was 82%. The distribution of plant residues was 76%, which is by 15% more than for spherical cut-out discs. The maximum ridgeness of the field surface in terms of cultivation with tolls equipped with disk-knife working bodies does not exceed 5.6 cm.

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Received for publication August 18, 2017
Accepted after corrections April 4, 2018