IMPACT OF THE PLOUGH BODY PARAMETERS ON THE SOIL TILLAGE EFFICIENCY

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Abstract. The main parameters of the plough body that determine the ploughing efficiency are the initial and the final soil slice lifting angles on the share-mouldboard surface, the angle of its horizontal generatrix, the radius of this surface and the working width of the body. By using analytical correlations derived as a result of theoretical research, a computer algorithm has been worked out for simulating the functions of the plough body and the forces exerted by soil upon the operating parts, as well as its draft resistance. These correlations allow to determinate the forces acting on the plough body and its draft resistance depending on the body parameters, as well as to evaluate their impact on the ploughing efficiency: energy and the fuel consumption and the quality of work. For economical ploughing the initial lifting angle of the soil slice (the angle between share and furrow bottom) must have a minimal value (28…32^{o}). If the speed increases, the optimum inclination value of the horizontal generatrix for the minimum draft resistance decreases. In loamy soils, when the operating speed is 1…3 m·s^{-1}, its optimum value on the initial part of the share-mouldboard surface is correspondingly 65…40^{o} to 33…25^{o}. To ensure sufficient turning of the slice, the angle of the top generatrix must not be less than 48^{o}. If the radius of the mouldboard increases, the draft resistance of the body increases, which is connected with increased partial resistance caused by the weight and adhesion of the soil. If the working width of the body is increased from 30 m to 50 m, the specific consumption of energy, fuel and the ploughing costs decrease (in loamy soil by 10…16%) but the labour efficiency correspondingly increases. The use of bodies having optimal parameters allows obtaining good ploughing quality, reduce draft resistance by 12…20% and correspondingly raise the efficiency, to save fuel and financial resources for ploughing.

Key words: plough body parameters, forces acting on the plough body, draft resistance, analytic correlations, optimisation of parameters.

Introduction

Ploughing is one of the most power-consuming and expensive processes in agricultural production. It is known from our previous investigation (Vilde, 1999, 2004; Rucins et al., 2005) that the draft resistance of ploughs and energy requirement for ploughing depend on the plough body parameters and on such soil properties as its hardness, density, friction and adhesion. However, there were no sufficient analytical correlations that would enable the determination of the impact of the plough body parameters on the draft resistance of the share-mouldboard surface and the plough body, as a whole, as well as on the ploughing quality and expenses depending on the body parameters.

The purpose of the investigations is to study the factors that determine the quality and energy requirement of ploughing, the impact of body parameters on it and to find technical solutions for its improvement.

Materials and methods

The objects of the research are the forces acting on the plough body and its draft resistance depending on the body design parameters, as well as the physical and mechanical properties of soil and the mode of operation. On the basis of the previous investigations (Vilde, 1999) a computer algorithm has been worked out (Rucins et al., 2005) for the simulation of the forces exerted by soil upon the operating (lifting and supporting) surfaces of the plough body, and the draft resistance caused by these forces (Fig. 1).

Results and discussion

Mathematical methods and computer algorithms worked out for the simulation of soil tillage processes allow calculating the forces acting upon the machine operating parts and their optimal design (including the plough body) for qualitative soil tillage with minimum energy consumption (Vilde, 1999, 2004; Rucins et al., 2004, 2005). According to this investigation the draft resistance R_x of the plough body is determined by the share cutting resistance R_{Px}, the resistance caused by weight R_{Gx} of the strip lifted, by the inertia forces R_{Jx}, by soil adhesion R_{Ax} and by weight R_{Qx} of the plough body itself (including a part of the weight of the plough). However, the latter is not dependent on the plough parameters.

$$R_x = \sum R_{ix} = R_{Px} + R_{Gx} + R_{Jx} + R_{Ax} + R_{Qx} . \quad (1)$$

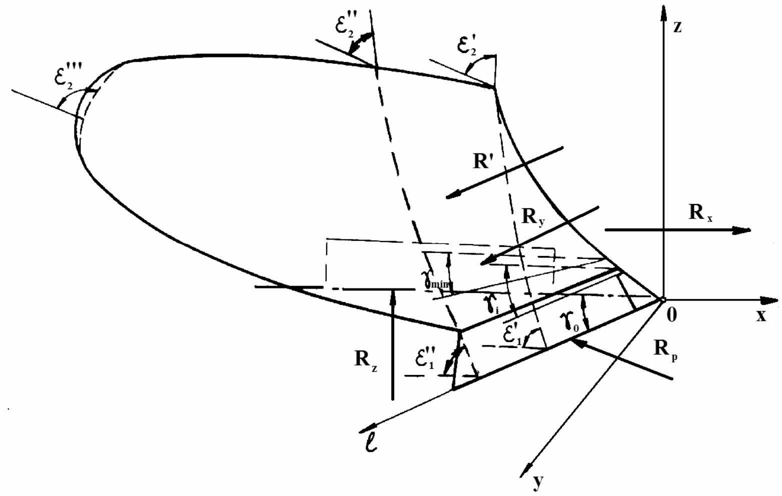

Fig. 1. **Scheme of the plough body, its parameters and acting forces**

The vertical reaction R_z and the lateral reaction R_y of the operating part are defined by the sum of corresponding partial reactions:

$$R_z = \sum R_{iz} \ ; \ R_y = \sum R_{iy} \tag{2; 3}$$

The total draft resistance R_x of the operating part is composed of the resistance of the working surface R_x' and the resistance of the supporting (lower and lateral) surfaces R_x'' :

$$R_x = R_x' + R_x'' = \sum R_{ix}' + f_0\left(\sum R_{iz} + \sum R_{iy} + p_{Axy}S_{xy} + p_{Axz}S_{xz}\right), \tag{4}$$

where f_0 – the coefficient of soil friction along the working and supporting surfaces of the operating part;
p_{Axy} and p_{Axz} – specific adhesion force, respectively, to the lower and the lateral supporting surfaces of the operating part;
S_{xy} and S_{xz} – the surface area of the lower and the lateral supporting surfaces of the operating part.

Cutting resistance R_{Px}' is proportional to soil hardness ρ_0 and the share edge surface area ω:

$$R_{Px}' = k_p \rho_0 \omega = k_p \rho_0 ib\,, \tag{5}$$

where k_p – the coefficient involving the impact of the shape of the frontal surface of the ploughshare edge;
i and b – the thickness and width of the edge.

It is evident from formula (5) that the friction of soil along the edge does not influence the cutting resistance of the edge.

At a sharp ploughshare (the rear bevel is absent):

$$R_{Pz} = 0\,. \tag{6}$$

At a blunt (threadbare) ploughshare having rear bevel the vertical reaction R_{Pz} on the hard soils can reach the summary value of vertical reactions, this summary value arising from other forces acting on the share-mouldboard surface (soil gravity and inertia) and the weight of the body Q.

At an inclined ploughshare a lateral reaction R_{Py} arises, its value being affected by the friction reaction:

$$R_{Py} = k_p \rho_0 ib \ ctg\left(\gamma_0 + \varphi_0\right), \tag{7}$$

where γ_0 – the inclination angle of the edge towards the direction of movement (the wall of the furrow);
φ_0 – the angle of friction.

Friction of soil along the ploughshare edge reduces the lateral pressure of the ploughshare (the pressure of the plough body against the wall of the furrow).

The resistance of the supporting surface

$$R''_{Px} = k_p \rho_0 ibf_0 \ ctg(\gamma_0 + \varphi_0) = F''_{Px}. \tag{8}$$

The total cutting resistance

$$R_{Px} = k_p \rho_0 ib[1 + f_0 \ ctg(\gamma_0 + \varphi_0)]. \tag{9}$$

The lateral cutting resistance of the knife is determined by formulae, similar to those for the cutting resistance from below. Consequently, similar to the above formulae will also be the formulae defining the impact of friction on the total resistance of the knife.

Forces caused by the weight of the lifting soil strip:

$$\begin{aligned} R'_{Gx} \approx q\delta g k_y r \sin^{-1}\gamma \ \{ & [(\sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma) e^{f_0 \sin\gamma(\varepsilon_1 - \varepsilon_2)} - \\ & - (\sin\gamma\cos\varepsilon_2 + \cos^2\gamma\sin^{-1}\gamma)]\cos\varepsilon_1 + \\ & + (\cos\varepsilon_1 e^{f_0 \sin\gamma(\varepsilon_2 - \varepsilon_1)} - \cos\varepsilon_2)(\cos\varepsilon_1 - f_0 \sin\varepsilon_1 \sin\gamma)^{-1} \cdot \\ & \cdot \sin\varepsilon_1 [\sin\varepsilon_1 \sin\gamma + f_0 (\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma)]\} \end{aligned} \tag{10}$$

$$R_{Gz} \approx q\delta gr \sin^{-1}\gamma(\varepsilon_2 - \varepsilon_1), \tag{11}$$

$$R_{Gy} \approx q\delta gr \sin^{-1}\gamma(\varepsilon_2 - \varepsilon_1)(\varepsilon_1 + 0.52) \ ctg\gamma, \tag{12}$$

$$R''_{Gx} = f_0 (R_{Gz} + R_{Gy}) = F''_{Gx}. \tag{13}$$

Forces caused by the soil inertia:

$$\begin{aligned} R'_{Jx} = q\delta v^2 k_y^{-1} \sin\gamma \{ & (\sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma) e^{f_0 \sin\gamma(\varepsilon_1 - \varepsilon_2)} - \\ & - (\sin\gamma\cos\varepsilon_2 + \cos^2\gamma\sin^{-1}\gamma) + (\cos\varepsilon_1 - f_0 \sin\varepsilon_1 \sin\gamma)^{-1} e^{f_0 \sin\gamma(\varepsilon_2 - \varepsilon_1)} \cdot \\ & \cdot \sin\varepsilon_1 [\sin\varepsilon_1 \sin\gamma + f_0 (\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma)]\} \end{aligned} \tag{14}$$

$$R_{Jz} = q\delta v^2 k_y^{-1} \sin\gamma \sin\varepsilon_2 e^{f_0 \sin\gamma(\varepsilon_2 - \varepsilon_1)}, \tag{15}$$

$$R_{Jy} \approx q\delta v^2 k_y^{-1} \sin\gamma\cos\gamma(1 - \cos\varepsilon_2), \tag{16}$$

$$R''_{Jx} = f_0 (R_{Jz} + R_{Jy}) = F''_{Jx}. \tag{17}$$

Forces caused by soil adhesion:

$$\begin{aligned} R'_{Ax} = p_A br \sin^{-1}\gamma (e^{f_0 \sin\gamma(\varepsilon_2 - \varepsilon_1)} - 1) \{ & \sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma + \\ & + (\cos\varepsilon_1 - f_0 \sin\varepsilon_1 \sin\gamma)^{-1} \sin\varepsilon_1 [\sin\varepsilon_1 \sin\gamma + f_0 (\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma)]\} \end{aligned} \tag{18}$$

$$R_{Az} = 0, \tag{19}$$

$$R_{Ay} \approx 0, \tag{20}$$

$$R''_{Ax} = f_0 (p_{Axy} S_{xy} + p_{Axz} S_{xz}) = F''_{Ax}, \tag{21}$$

where: q – the cross section area of the strip to be lifted;
δ – the density of soil;
k_y – the soil compaction coefficient in front of the operating part;
f_0 – the soil friction coefficient against the surface of the operating element;
v – the speed of the movement of the plough body;
p_A – the specific force of soil adhesion to the operating surface;

b – the surface width of the soil strip;
ε_1 and ε_2 – correspondingly the initial and the final angles of the lifting (share-mouldboard) surface;
γ – the inclination angle of the horizontal generatrix towards the direction of movement (the wall of the furrow);
g – acceleration caused by gravity ($g = 9.81$).

The soil friction coefficient and the specific force of soil adhesion are not constant values. Their values decrease with the increase in speed (Vilde et al., 2004 [4]). This is considered in the calculations. The resistance of the supporting surfaces of the plough body depends on the values of the reacting forces. Yet their value is dependent, in many respects, on the manner of unification and perfection of the hydraulically mounted implements of the tractor. The vertical reaction of the plough with modern tractors having power regulation is transferred to the body of the tractor, and it affects the plough resistance to a considerably lesser degree (Vilde et al., 2004 [5]).

The obtained correlations (5 – 21) allow determination of the forces acting on the plough body and its draft resistance depending on the body parameters, as well as evaluation of their impact on the ploughing efficiency: energy and the fuel consumption and the quality of work. These parameters are: the initial and the final angles of the lifting (share-mouldboard) surface ε_1 and ε_2; the inclination angle of the horizontal generatrix towards the direction of movement (the wall of the furrow) γ_i (see Fig. 1) and regularity (law-governed nature) of its variation; the thickness of the share edge i; the radius r of the lifting (share-mouldboard) surface and the area of the lifting and supporting surfaces $b \cdot 2\pi r(\varepsilon_2 - \varepsilon_1)$, S_{xy} and S_{xz}.

The materials of the calculations carried out using the correlations indicated above present the values and regularity of the changes in the forces acting on the share-mouldboard and the supporting surfaces, the draft resistance of the share-mouldboard and the supporting surfaces, as well as the total resistance of the plough body and its components under working conditions depending on the body parameters and the working speed. Possibilities to reduce the tillage energy requirement have been clarified.

The obtained materials show that by increasing the initial lifting angle ε_1 (inclination angle of share toward furrow bottom) the draft resistance increases. For economical ploughing the initial lifting angle of the soil slice (the angle between share and furrow bottom) must have a minimal value – 24…30°. The smallest inclination angle is not desirable because by wear out of the share there is a possibility at the blunt (threadbare) ploughshare to obtain a rear bevel, which can hinder the plough body from going into soil. This phenomenon is observed with the Kverneland plough bodies No. 8 having a 20° inclination angle of their outer part.

More complicated is the impact of the inclination angle γ of the horizontal generatrix. Depending on the working speed, the change of its value can impact the value of the draft resistance positively or negatively, that is, to decrease or increase the draft resistance. When the inclination (angle γ) of the generatrix is increased, the resistances, because of the soil weight and adhesion, fall but the resistance due to the inertia forces increases, particularly when operating at higher speeds. The decrease of the first ones can be explained by the fact that its length decreases at a steeper share-mouldboard surface, and, because of this, there is a decrease in the mass of soil slipping along it. Decreasing the area of its surface leads to a lower resistance due to soil adhesion. As a result, the total draft resistance of the share-mouldboard surface shows a marked minimum, which, at a greater operating speed, moves towards lower inclination values of the horizontal generatrix. Thus, if the speed increases, the optimum inclination value of the horizontal generatrix for the minimum draft resistance decreases. In loamy soils, at the initial lifting angle $\varepsilon_1 = 30°$, when the operating speed is 1…3 $m \cdot s^{-1}$, its optimum value for the share-mouldboard surface on its initial part is correspondingly 40…25°, for the plough body, as a whole, they can be 65…33° (if working in a floating mode). When the vertical reaction of the plough (or part of it) with modern tractors having power regulation is transferred to the body of the tractor, the optimal inclination value of the horizontal generatrix obtains medium indices – approximately 50…30°. At contemporary ploughing speeds 2…2.5 $m \cdot s^{-1}$ (7…9 $km \cdot h^{-1}$) the optimal inclination of the horizontal generatrix on the initial part of the share-mouldboard surface is 38…34° (Vilde, 1999).

To ensure sufficient turning of the slice, the angle of the top generatrix must not be less than 48^o.

If radius r of the mouldboard increases, the draft resistance of the body increases, which is connected with increased partial resistance caused by the weight and adhesion of the soil. For general purpose ploughs its value varies within the range of 0.5 m.

The working width of the body influences its draft resistance too. If the working width of the body is increased from 30 cm to 50 cm (at constant frontal width of the share), the specific consumption of energy, fuel and the ploughing costs decrease (in loamy soil by 10…16%) but labour efficiency correspondingly increases (Rucins at al., 2005[7]).

The cutting resistance is proportional to the thickness of the share edge. To obtain a low value of the cutting resistance, its value must be minimal – 2…3 mm. In the ploughing process the share wears out and the thickness of its edge increases to 5 mm, and more. This causes increased draft resistance, especially in hard (dry loamy) soils. Therefore self-sharpening shares are better which do not lose their sharpness in ploughing process.

The conducted investigations show that those ploughs generally meet the requirements mentioned above which have bodies with gently sloping semi-helicoidal or helicoidal share-mouldboard surfaces, such as, the Kverneland plough body No. 8.

There may be cases (at quite a flat share-mouldboard surface) when the draft resistance in wet loamy soils does not increase but even decreases whereas its speed increases (within the range of 1…2 m·s^{-1}). Such a phenomenon may occur when the decrease in resistance, due to the lower friction coefficient and specific soil adhesion, proceeds more intensely than the growth in the resistance caused by the soil inertia forces within the given range of speeds.

The impact of the soil-metal friction upon the plough body draft resistance is significant. It may reach 50…60% of the total draft resistance including the resistance of the supporting surfaces (25…30%) (Vilde et al., 2004 [4]). Therefore measures will be taken to diminution it, for example, using antifriction materials (Teflon or others).

In such a way, the deduced analytical correlations and the developed computer algorithm enable simulation of the soil coercion forces upon the share-mouldboard surface of the plough body, taking into consideration its draft resistance, as well as determination of the optimum parameters at minimum resistance.

Conclusions

1. The deduced analytical correlations and the developed computer algorithm enable the simulation of the soil coercion forces upon the operating surfaces of the plough body, determination of its specific draft resistance depending on the body design, the working parameters and soil properties and motivation of the optimal values of parameters.
2. Presentation of the draft resistance of the plough body as the sum of its components – the cutting resistance of the strip, the resistance caused by its weight, the soil inertia forces and adhesion – allows analysis of the forces acting upon the share-mouldboard surface, finding out the character of their changes depending on speed and the parameters of the surface, and assessment of their ratio in the total resistance.
3. The main parameters affecting the ploughing efficiency are: the initial and the final angles of the lifting (share-mouldboard) surface; the inclination angle of the horizontal generatrix towards the direction of the movement and the regularity of its variation; the thickness of the share edge; the radius of the lifting surface and the area of the lifting and supporting surfaces.
4. Increase in the inclination of the horizontal generatrix leads to a decrease in the draft resistance caused by the weight and adhesion of soil but it increases the resistance caused by inertia forces, particularly, when the speed increases. The inclination of the generatrix (the edge of the share) does not affect the cutting resistance of the strip.
5. In loamy soils, when the speed grows from 1 to 3 m·s^{-1}, the optimum value of the inclination angle between the horizontal generatrix of the share-mouldboard surface and the wall of the furrow decreases from 65…40^o to 33…25^o. At the ploughing speed 2…2.5 m·s^{-1} it is 38…34^o.
6. To ensure sufficient turning of the slice, the angle of the top generatrix must not be less than 48^o.

7. Increasing the working width of the body from 30 cm to 50 cm (at a constant frontal width of the share), the specific consumption of energy, fuel and the ploughing costs decrease (in loamy soil by 10…16%) but the labour efficiency correspondingly increases.
8. The draft resistance of the supporting surfaces is considerable. It can reach 25…30% of the total plough body draft resistance, or 42…54% of its share-mouldboard draft resistance.
9. The impact of the soil-metal friction upon the draft resistance of the plough body is significant. It may reach 50…60% of total draft resistance including the resistances of the supporting surfaces (25…30%). Therefore measures will be taken to diminution it, for example, using antifriction materials (Teflon or others).
10. The optimal values of the main parameters of the bottoms for contemporary ploughs are; the inclination angle of share towards the furrow bottom – 28…32^o; the inclination angle of the horizontal generatrix towards the furrow wall on the initial part of the share-mouldboard surface – 34…38^o, on the top – not less than 48^o; the working width of the bottom – 45…50 cm.
11. The use of bodies having optimal parameters allows obtaining a good ploughing quality, reduction of the draft resistance by 12…20% and a corresponding rise in the efficiency, saving fuel and financial resources for ploughing.

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