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Theoretical analysis of interaction of disc coulters and straw residues under no-tillage conditions

E. Šarauskis[1,*], K. Romaneckas[2], A. Sakalauskas[1], E. Vaiciukevičius[1], K. Vaitauskiene[1], D. Karayel[3] and R. Petrauskas[1]

[1]Institute of Agricultural Engineering and Safety, Aleksandras Stulginskis University, Studentu 15A, LT-53361 Akademija, Kauno distr., Lithuania; [*]Correcpondence: egidijus.sarauskis@asu.lt
[2]Institute of Agroecosystems and Soil Science, Aleksandras Stulginskis University, Studentu 11, LT-53361 Akademija, Kauno distr., Lithuania; [3]Department of Agricultural Machinery, Faculty of Agriculture, Akdeniz University, TR-07058 Antalya, Turkey

Abstract. The article presents the theoretical aspects of disc coulters working process under no-tillage conditions. Under no-tillage conditions, effective operation of disc coulters is impeded by plant residues. In the interaction of a disc coulter, plant residues and soil surface, the disc coulter may cut the plant residues, roll over them or press them into the furrow being formed in the soil. The objective of the research is to theoretically study the process of straw cutting by disc coulters under no-tillage conditions and to substantiate the main parameters acting upon the cutting force. Theoretical studies established the dependency according to each the extent of the straw cutting force depends on the disc coulter blade sharpening angle, blade thickness and disc coulter blade length, straw normal stresses, friction coefficient, elastic modulus, straw diameter, its compression path, and other parameters. On the basis of calculations, it was found that if the disc coulter blade sharpening angle is increased by one degree, the cutting force sufficient to cut wheat straw can be reduced by 6.5 N, and reducing the disc coulter blade thickness by one millimetre would allow reducing the cutting force by 12.5 N.

Keywords: disc coulter, soil, plant residues, straw cut, no-tillage.

INTRODUCTION

Minimum-tillage and no-tillage methods have been widely implemented in Northern and Western European countries. Taking over experience of other European countries, the Baltic countries apply tillage and sowing technologies, which have numerous economic and environmental advantages, increasingly broadly. Taking into account the fact that ploughing is a low-efficient, expensive and most energy-consuming way of tillage, minimum-tillage and sowing technologies allow saving time, reducing fuel consumption, and cutting the cost of agricultural production (Linke, 1998; Šarauskis et al., 2012). The attractiveness of these technology increases even further when their positive impact on the environment is taken into consideration. As tillage intensity is reduced, riding over the soil decreases, upper and deeper layers of the soil are compacted less severely, soil erosion, elution of the fertile soil layer and chemical substances, and crop destruction and water contamination are reduced. Abandoning of soil tillage results in a several-fold increase in the number of soil biopores, improvement of the plant root system development and air and water filtration. When the surface of soil is covered with plant residues, a greater amount of rainfall can be absorbed, the soil surface crust is formed not so quickly after a heavy rain, moisture is retained better, and vegetation is exposed to lower stress under dry climatic conditions (Soane et al., 2012).

The most important task of the non-tillage and sowing process is to insert plant seeds evenly, at an established depth and at desired distances. The sowing depth is highly dependent on the seedbed preparation quality. The sowing place is on the junction of the atmosphere and soil surface exposed to various chemical, biological, mechanical, weather, and other factors (Romaneckas et al., 2009, Šarauskis et al., 2009; Rusu et al., 2011). Therefore, in order to ensure high-quality sowing technological process, it is very important to have good knowledge of and properly select the design of working parts and technological operating parameters (Karayel & Šarauskis, 2011).

In order to ensure an effective technological process of sowing into minimally tilled or no-tilled soil, grounds should be laid as early as at the time of harvesting. Harvest losses, cutting length of plant residues and uniformity of their spreading on the surface depend on the design of the operating parts of the harvester and technological operating parameters. The uniformity of the spreading of chaff emitted from the harvester also have a considerable impact on further tillage and sowing operations (Linke, 1996; Soane et al., 2012).

The layer of plant residues on the soil surface hinders proper carrying out of the sowing operating technological process. The thicker layer of plant residue clogs sowing coulters thus causing seeds to be inserted uniformly and at different depths (Morris et al., 2010). That is why sowers intended for sowing into non-tilled soils most commonly use disc coulters of various shapes. Considering the soil density and hardness, disc coulters can cut plant residues, roll over them, or to press them into the furrow made in the soil.

In previous studies (Šarauskis et al., 2005), it was found that in order to prevent disc coulters from being blocked with plant residues, the diameter of coulters should be sufficiently large (about 50–70 cm). Small diameter (15–30 cm) disc coulters, depending on the thickness of the layer of plant residue on the soil surface, may start pushing plant residues in front of the coulter. It is not reasonable to use coulters of very large diameters because the soil resistance force acting upon the coulters increases and, therefore, requires a greater pressing force acting upon the coulters and results in increased resistance of the entire machine to traction. In order to reduce the diameter of the disc coulters and ensure that they are not blocked with plant residues, disc coulters are made with jagged, wavy, corrugated and other types of blades.

Plant residues will not be pushed forward if the pinch angle of plant residues between the tangent of the disc coulter blade and soil surface is less than the sum of the friction angles between the disc coulter blade and plant residues and between plant residues and soil surface (Šarauskis et al., 2005).

There is currently a lack of knowledge on the progress of plant residues cutting technological process, on the forces that act in the course of the interaction of disc coulters and plant residues, and what determines the extent of the cutting force.

The objective of the research is to theoretically study the process of straw currying by disc coulters under no-tillage conditions and to substantiate the main parameters acting upon the cutting force.

Theoretical consideration

When a disc coulter, rolling over the surface of non-tilled soil, encounters plant residues (hereinafter referred to as 'straw'), it starts pressing and compressing them. In order to enable the disc coulter blade to cut the straw, the hardness of the non-tilled soil should be greater than the normal stresses of the straw. The cutting force (F_{pj}) should be maximal, i.e. greater than the straw resistance forces (Fig. 1).

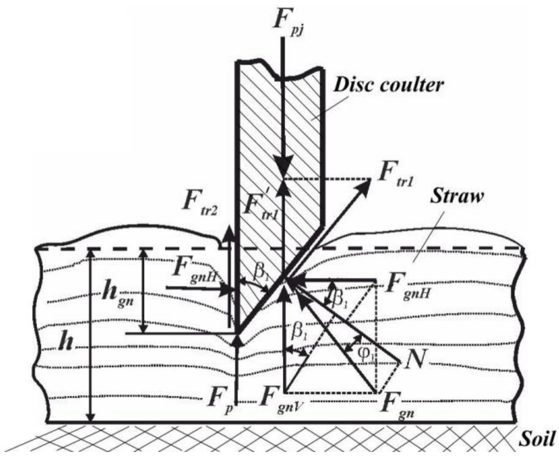

Figure 1. The diagram of the forces acting upon the disc coulter blade at the time of straw cutting: F_p – the resistance force acting upon the disc coulter blade, in N; F_{gnV} – the vertical force of resistance to straw compression, in N; F_{gnH} – the horizontal force of resistance to straw compression, in N; β_1 – disc coulter blade sharpening angle, in degrees; φ_1 – friction angle of the disc coulter rake and straw, in degrees; h_{gn} – straw compression path, in mm; h – diameter of the straw being cut, in mm; F_{tr1} – the friction force acting upon the disc coulter rake, in N; F'_{tr1} – the vertical projection of friction force, in N; F_{tr2} – the friction force acting upon the disc coulter side, in N; N – the normal force acting upon the disc coulter rake, in N; F_{pj} – the cutting force, in N.

The resistance force acting upon the disc coulter blade (F_p) is calculated in accordance with the following formula (Juodis, 1989; Čižas, 1993):

$$F_p = S\sigma = \delta \Delta l \sigma \quad (1)$$

where S – area of the disc coulter blade, in mm^2; σ – normal stresses of straw, in MPa; δ – thickness of the disc coulter blade, in mm; Δl – length of the disc coulter blade at the time of contact with straw, in mm.

Normal stresses of straw depend on the structure and properties of the straw. It was found on the basis of experimental studies that normal stresses of wheat straw range from 2.05 to 2.91 MPa (Reznik, 1975).

The disc coulter blade rake is acted upon by the normal force (*N*), which can be calculated as follows:

$$N = F_{gnV} \sin \beta_1 + F_{gnH} \cos \beta_1 \tag{2}$$

or alternatively

$$N = \sqrt{F_{gnV}^2 + F_{gnH}^2} \cos \varphi_1 , \tag{3}$$

where F_{gnV} – the vertical force of resistance to straw compression acting upon the coulter blade, in N; F_{gnH} – the horizontal force of resistance to straw compression acting upon the coulter blade, in N; β_1 – disc coulter blade sharpening angle, in degrees; φ_1 – friction angle of the disc coulter rake and straw, in degrees.

The disc coulter blade rake is acted upon by the friction force F_{tr1}, and the coulter side is acted upon by the friction force F_{tr2}:

$$F_{tr1} = Nf , \tag{4}$$

$$F_{tr2} = F_{gnH} f , \tag{5}$$

where $f = \tan \varphi_1$ – straw and disc coulter friction coefficient.

The vertical friction force projection $F_{tr1}^{'}$ is calculated as follows:

$$F_{tr1}^{'} = F_{tr1} \cos \beta_1 . \tag{6}$$

Upon substituting the expressions 4 and 2 into Equation 6 and transformed, the following is obtained:

$$F_{tr1}^{'} = f(\frac{1}{2} F_{gnV} \sin 2\beta_1 + F_{gnH} \cos^2 \beta_1) . \tag{7}$$

In order for the disc coulter to cut the straw, the cutting force must be greater than the sum of the resistance forces acting in the vertical direction:

$$F_{pj} = F_{pj\max} > F_p + F_{gnV} + F_{tr1}^{'} + F_{tr2} . \tag{8}$$

The forces F_{gnV} and F_{gnH} can be calculated upon determining the elementary compressive forces dF_{gnV} and dF_{gnH}.

The vertical force of resistance to compression is equal to:

$$F_{gnV} = S\sigma \,. \tag{9}$$

The straw compression path condition:

$$h_{gn} = \frac{b_p}{\tan\beta_1}, \tag{10}$$

where b_p – disc coulter thickness, in mm.

The area of the disc coulter blade S, which is acted upon by the vertical force of resistance to compression F_{gnV}, is calculated in accordance with the following formula:

$$S = \Delta l h_{gn} \tan\beta_1, \tag{11}$$

where h_{gn} – straw compression path, in mm.

According to Hooke's law, straw compressive displacement is proportional to the load, and the strain is proportional to stresses (Čižas, 1993). The relative compressive deformation is equal to:

$$\varepsilon = \frac{\sigma}{E_T}, \tag{12}$$

where ET – elasticity modulus, in MPa.

The relative compressive deformation expressed through the elementary compression path of the straw being cut is determined as follows:

$$\varepsilon = \frac{h_{gnv}}{h}, \tag{13}$$

where h_{gnv} – elementary compression path of the straw being cut, in mm; h – diameter of the straw being cut, in mm.

Upon substituting the expressions of the area of the disc coulter blade (S) and straw normal stresses (σ) into Equation 9, the elementary vertical force of resistance to straw compression is calculated:

$$dF_{gnV} = \Delta l E_T \varepsilon dh_{gn} \tan\beta_1 \,. \tag{14}$$

Upon substituting the relative compressive deformation (ε) into Equation 14 and integrating it, the vertical force of resistance to compression acting upon the disc coulter blade rake is equal to:

$$F_{gnV} = \Delta l \frac{E_T}{2h} h_{gn}^2 \tan\beta_1 . \quad (15)$$

The horizontal force of resistance to straw compression is calculated in the same manner, by using the elementary forces:

$$dF_{gnH} = \varepsilon_1 E_T \Delta l d h_{gn} , \quad (16)$$

where ε_1 – relative straw compressive deformation in the horizontal direction.

The relative straw compressive deformation in the horizontal direction (ε_1) is equal to:

$$\varepsilon_1 = \varepsilon\mu , \quad (17)$$

where μ – Poisson's ratio.

Upon substituting the expressions 17 and 13 into Equation 14 and integrating it, the vertical horizontal force of resistance to straw compression acting upon the disc coulter blade rake is as follows:

$$F_{gnH} = \mu \frac{E_T}{2h} \Delta l h_{gn}^2 . \quad (18)$$

Upon substituting the expressions of the resistance forces acting in the vertical direction in Equation 8, the following was obtained:

$$F_{pj} = F_{pj\max} > \delta\Delta l\sigma + \frac{E_T h_{gn}^2 \Delta l}{2h} \tan\beta_1 + \frac{f\mu E_T h_{gn}^2 \Delta l}{2h} + \\ + f\left(\frac{1}{2} \frac{E_T h_{gn}^2 \Delta l}{2h} \tan\beta_1 \sin 2\beta_1 + \frac{\mu E_T h_{gn}^2 \Delta l}{2h} \cos^2\beta_1 \right). \quad (19)$$

Upon transforming Equation 19, the straw cutting force (F_{pj}) is equal to:

$$F_{pj} = F_{pj\max} > \delta\sigma\Delta l + \frac{E_T h_{gn}^2 \Delta l}{2h} [\tan\beta_1 + f(\sin 2\beta_1 + \\ + \mu(1 + \cos^2\beta_1))]. \quad (20)$$

Equation 20 shows that the straw cutting forces are influenced significantly by the structural parameters of the disc coulter (β_1, δ and Δl), straw physical and mechanical properties (E_T, μ, f and σ), straw diameter (h) and its compression path (h_{gn}).

If straw physical and mechanical properties, straw diameter and its compression path are rationally assessed, it is possible to establish the dependency of the extent of the cutting force from the disc coulter blade sharpening angle and blade thickness (Fig. 2).

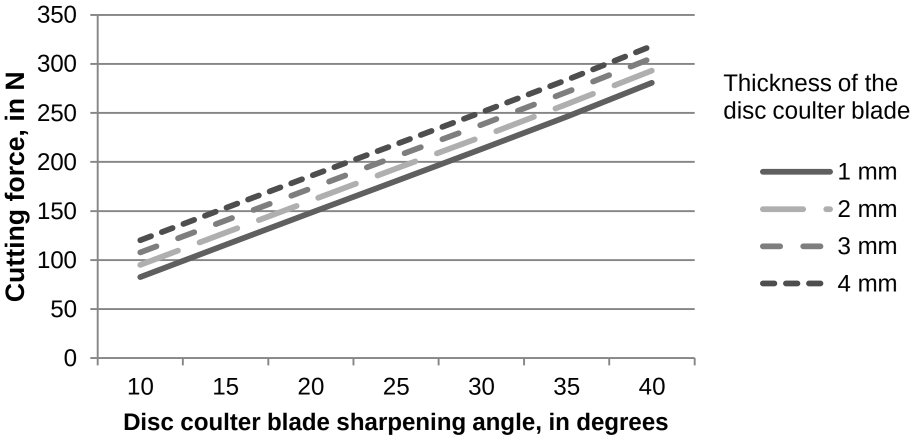

Figure 2. Dependency of the extent of the cutting force from the disc coulter blade sharpening angle and blade thickness when wheat straw $\sigma = 2.5$ MPa, $E_T = 28$ MPa, $f = 0.35$, $\mu = 0.025$, $h = 5$ mm, $h_{gn} = 4$ mm, $\Delta l = 5$ mm.

As the disc coulter blade sharpening angle is reduced, the extent of the curring force decreases. Upon assessment of various disc coulter and straw parameters, it was established that reducing the disc coulter blade sharpening angle by one degree, the cutting force can be reduced by 6.5 N. Under normal conditions, the disc coulter blade sharpening angle could be around 20°. As the disc coulter blade thickness is reduced, the cutting force also decreases.

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CONCLUSIONS

1. Under no-tillage conditions, effective operation of disc coulters is impeded by plant residues. In the interaction of a disc coulter, plant residues and soil surface, the disc coulter may cut the plant residues, roll over them or press them into the furrow being formed in the soil.
2. The extent of the straw cutting force depend on the structural parameters of the disc coulter (β_1, δ and Δl), straw physical and mechanical properties (E_T, μ, f and σ), straw diameter (h) and its compression path (h_{gn}).
3. If the disc coulter blade sharpening angle is reduced by one degree (when $\sigma = 2.5$ MPa, $E_T = 28$ MPa, $f = 0.35$, $\mu = 0.025$, $h = 5$ mm, $h_{gn} = 4$ mm, and $\Delta l = 5$ mm), the cutting force can straw cutting can be reduced by 6.5 N. If the disc coulter blade thickness is increased by one millimetre, under the same conditions, the cutting force should be increased by 12.5 N.

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