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The method of determination of the safety zone between the rototiller cover and rotor

MICHAŁ SYPUŁA, JACEK KLONOWSKI, TOMASZ NOWAKOWSKI, ALEKSANDER LISOWSKI, JAROSŁAW CHLEBOWSKI, ADAM STRUŻYK, ADAM ŚWIĘTOCHOWSKI
Department of Agricultural and Forest Machinery, Warsaw University of Life Sciences – SGGW

Abstract: *The method of determination of the safety zone between the rototiller cover and rotor.* The objective of the study was to develop an analytical method of determination of the safety zone between the rear cover and the rotor of the rototiller for various cover types. Using the sizes and relationships between characteristic points of the rotor and the cover of the machine, an algorithm was developed to calculate the safety zone, which is applicable to the entire range of settings of the rear cover and the working depth. The safety zone was assumed to be the horizontal distance between the end of the rear cover of the rotor from the path of movement of the cutting blades, according to the requirements of the harmonized standard EN ISO 4254-5:2009+AC 2011. Determination of this distance requires measurement of: the cover mounting height, the length of the section connecting the rotor rotation axis and the rear edge of the cover and the diameter of the rotor with knives. The safety zone within the area of the rear cover of the machine was verified for three types of rototillers with varying cover structures. The analysis conducted showed that use of a two-component rear cover with an articulated mechanism allows for maintaining of the required safety zone regardless of the positioning of the cover and the working depth.

Key words: rototiller, rotor cover, safety zone, requirements

INTRODUCTION

An advantage of rototilllers is the possibility of preparing soil for sowing in a single passage, without the need of additional cultivation, which is necessary when using passive cultivation tools [Gopal et al. 2012]. For this reason, they are very popular in gardening and in spring cultivation of the soil after the autumn ploughing, and in grinding of turf in the meadows in cultivation after long-term plantings, mixing of fertilizers with the soil, crushing of clods and eliminating weeds [Bernacki 1981, Gach et al. 1991, Waszkiewicz and Kuczewski 1996, Gopal et al. 2012, Prasad et al. 2014]. As the tractor wheels operate almost without sliding, the effect of substantial reduction of loss in propulsion power is achieved [Shinners et al. 1993]. Rototillers, despite substantial demand for energy, are often an alternative for passive cultivation tools, particularly for deep cultivation [Majewski et al. 1982, Buliński and Sergiel 2014, Powałka and Buliński 2014a, b]. Davis et al. [1982]

provide that the power requirement for preparation of the same sowing layer for a given degree of soil grinding using rototiller is usually greater (1 to 1.5 times) in comparison with mouldboard ploughs with secondary tillage tools. During rototiller operation, the desirable effect of secondary tillage is achieved thanks to such processes as cutting, grinding, turning and moving of the soil [Salokhe and Ramalingam 2003].

Energy consumption and quality of work of the rototiller is influenced by many factors, including knife configuration, direction of rotation, ratio of the peripheral speed of the rotor to the forward movement speed of the machine, depth of cultivation and physical condition of the soil [Davis et al. 1982, Waszkiewicz and Miszczak 1986].

In order to reduce the machine clogging tendency, which, however, leads to leaving of more large clods, it is possible to use a configuration with two knives per flange as an alternative for the standard three-knife configuration [Celik and Altikat 2008].

Additional aeration of the soil can be achieved by setting the appropriate height of the rear cover, against which the clods are crushed upon impact.

The rear cover is thus a significant component of the rototiller, and its mounting height exerts significant impact on soil aeration.

One of the most significant requirements to be met by rototillers is protection against accidental contact with the rotating knives. Due to movement of the working rotor and the possibility of discharge of objects, and for the sake of proper functioning of the rototiller, the cover suspended from the rear of the machine should be properly designed.

When designing a rototiller, it is necessary to take into account the provisions of the harmonized standard EN ISO 4254-5:2009+AC 2011, which are the most detailed and should be used in the first place. The standard specifies the safety requirements and the mode of their verification for cultivation machines with active working units.

Application of harmonized standards to research allows for the quickest and simplest determination of whether a given product is consistent with the basic requirements [Klembalska 2008, 2010]. The principle of presumption of conformity is applied, according to which it is assumed that a product manufactured in accordance with the harmonized standards and the machine directive meets the basic requirements of the EU directive [Dyrektywa 2006/42/WE, Klembalska 2011].

At the stage of safety research for rototillers, a practical problem encountered is the mode of measurement of the minimum distance between the end of the rear cover of the rotor and the trajectory of movement of the cutting knives in accordance with the provisions of the harmonized standard EN ISO 4254-5:2009+AC 2011. This is due to the irregular shape of the knife and difficulties with exact direct measurement of this distance for varying settings of the cover height.

The aim of the study was to develop a method for determination of the safety zone between the rear cover edge and the rototiller rotor knives for various types of covers used in these machines.

MATERIAL AND METHODS

The requirements specified in the harmonized standard EN ISO 4254-5:2009+AC 2011 define the values of the required cover positioning parameters for its varying setting; however, the standard does not specify the detailed structural solutions and they do not indicate the test method. At the stage of research and assessment of compliance with the requirements concerning the minimum horizontal distance between the relative rotor movement trajectory and the lower edge of the rear cover (Fig. 1), treated as the danger zone, specification of this value is problematic, since it is not possible to determine precisely the movement trajectory of the cutting blades due to the complex shape resulting from its bending. This minimum distance (without taking into account the soil penetration depth of the knives) should be no less than 200 mm while the cover is set at the height up to 400 mm from the knife blade edge in its lower position. When the cover is located at a greater height, this distance should not be less than based on the relationship presented in Figure 1 and Table 1.

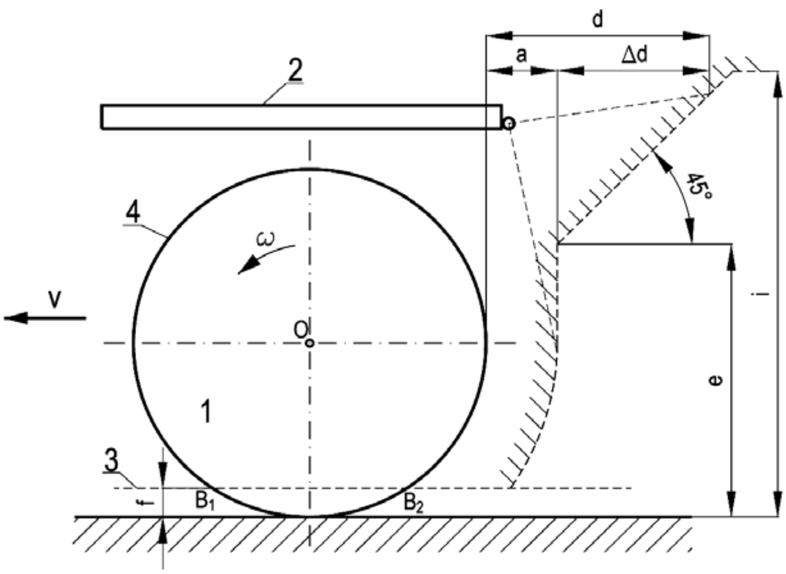

FIGURE 1. Diagram of the required safety zone between the rotor movement trajectory and the lower edge of the rear cover: 1 – rotor, 2 – frame, 3 – ground surface, 4 – rotor movement trajectory, *v* – direction of movement, *f* – rotor working depth

TABLE 1. The minimum horizontal distance between the rotor movement trajectory and the lower edge of the rear cover (on the basis of requirements of EN ISO 4254-5:2009+AC 2011)

Vertical distance according to figure 1	Horizontal distance between rotor movement trajectory and cover edge
For $e - f \leq 400$ mm	$d = a \geq 200$ mm
For $i - f \leq 800$ mm	$d \geq 200$ mm + Δd – according to Figure 1 and equation (1)

If the end of the rear cover is set at the height of 400 to 800 mm from the knife blade edge in the lowest position, according to Figure 1, the safety distance in this regard should be increasing linearly as the height changes. This can be presented in form of the following equation:

$$\Delta d = d - a = i - e \qquad (1)$$

where:
d – required distance from knife movement trajectory to a lower edge of cover for 400< and ≤800 mm;
a – required distance from knife movement trajectory to a lower edge of cover for $0 \leq e \leq 400$ mm;
i – height of position of the end of rear cover from ground within the range of 400–800 mm;
e – height of position of the end of rear cover from ground within the range of 0–400 mm.

In the case if the rotor is penetrating the soil to the depth of f, the height of positioning of the end of the cover refers not to the base (the lower positioning of the knife), but to the soil surface level. The required safe distance between the end of the cover and the knife movement trajectory is specified in the same manner. However, it is necessary to take into account the requirements of applicability of other ranges of positioning of the rear cover end, which should be as follows: for $a - 0 \leq e - f \leq 400$ mm and for d: $-400 < i - f \leq 800$ mm.

Checking of the requirements presented in Table 1 takes place under laboratory conditions.

The safety zone can be determined indirectly by measuring the length of section (l), connecting the rotor axis of rotation and the rear edge of the cover and the vertical distance between the lower edge of the rear cover (i) and the ground surface (Fig. 2).

Examining the right-angled triangle OAA_2 (Fig. 2), it is possible to come up with:

$$l^2 = l_1^2 + \left(\frac{d_w}{2} - i\right)^2 \qquad (2)$$

where:
l – distance between rotor axis and the end of the rear cover [mm];
l_1 – horizontal distance between rotor axis and the end of the rear cover [mm];
d_w – rotor diameter [mm].

Then it is possible to determine the horizontal distance between the rotor axis and the lower edge of the rear cover (l_1):

$$l_1 = \sqrt{l^2 - \left(\frac{d_w}{2} - i\right)^2} \qquad (3)$$

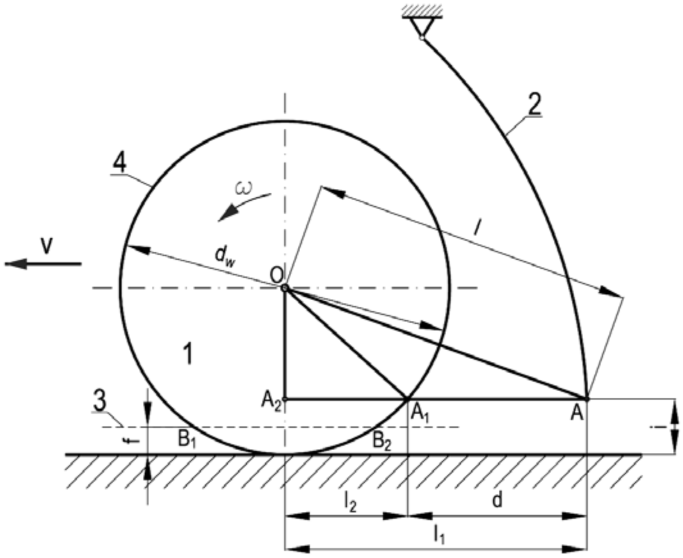

FIGURE 2. Determining of the safety zone between the rotor movement trajectory and the lower edge of the rear cover

Depending on the working depth set, the working knives will penetrate the soil to the depth (*f*), establishing on the upper surface of the soil a chord of the circle, described by the knife tip movement. In practice, for typical working conditions, the depth of setting of the rototiller knives is lesser than the rotor radius [Hendrick and Gill 1971, Prasad et al. 2014].

Similarly, considering the triangle OA_1A_2 (Fig. 2), it is possible to come up with:

$$\left(\frac{d_w}{2}\right)^2 = l_2^2 + \left(\frac{d_w}{2} - i\right)^2 \tag{4}$$

where:
l_2 – horizontal distance between rotor axis and the end of rotor trajectory at point A_1 [mm].

After transformation, this distance is:

$$l_2 = \sqrt{id_w - i^2} \tag{5}$$

The relationship, described by equation (5), is applicable, if the cover is set at height (*i*) not greater than the rotor radius.

When the end of the cover is set above the rotor rotation axis $i > dw \cdot 0.5$, the smallest horizontal distance can be observed between the end of the cover and the knife movement trajectory at the height of the rotor axis, which determines the safety zone, while horizontal distance from the rotor axis to this point will be equal to the rotor radius:

$$l_2 = \frac{d_w}{2} \tag{6}$$

Figure 2 indicates that lengths of sections l_1 and l_2 depend on positioning of the cover – they do not change along with the working depth. The difference between lengths of sections l_1 and l_2 is the sought minimum horizontal distance between the rotor movement trajectory and the lower edge of the cover:

$$d = l_1 - l_2 \quad (7)$$

In order to determine this length, we thus need the following parameters: the cover setting height (*i*), length of the section connecting the rotor rotation axis and the rear edge of the cover (*l*) and rotor diameter (d_w). These parameters are determined experimentally.

The use of this algorithm is applicable for the entire range of settings of the rear cover and the working depth of the machine.

Taking into account the shape of the knives and the way, in which they are fixed to the rotor disks, and hindered access to the area between these components, as well as differences between cover types, direct measurement of the diameter along the external surface of the rotor knives is complicated. This diameter can be determined indirectly by measuring the diameter of the rotor shaft and the distance between the shaft perimeter and the external knife surface. For this purpose, a rangefinder was set next to the rototiller raised to the mechanical linkage of the tractor and stabilized with supports, and the stream of light was directed up to the external surface of the rotor shaft; by moving the rangefinder perpendicular to the rotor axis, the minimum distance between the base level and the rotor shaft was established. At the same setting of the rototiller and the rangefinder, the rotor was turned manually, determining the minimum distance between the base and the external knife surface. The difference between the two measured values is the maximum distance between the external surface of the knife and the rotor shaft perimeter. The rotor shaft diameter was measured directly using a slide calliper. Thus, the knife trajectory diameter in rotational movement of the rotor was calculated as the total of the diameter of the rotor shaft and double distance between the knife external surface and the rotor shaft perimeter.

The safety zone in the area of the rear cover of the machine was verified, using three types of rototillers, varying with regard to cover structure (Fig. 3) and using the standard EN ISO 4254-5:2009+AC 2011.

Individual distance measurements were performed using a measuring tape of measuring range of 5 m at the accuracy of 1 mm, a slide calliper at accuracy of 0.05 mm and a rangefinder at the accuracy of 1 mm.

The rototiller rotor (Fig. 3a) is covered from the top with a fixed cover, and with a suspended cover from the rear. The rotor diameter is 530 mm. For this system, as the rear cover is raised, its distance from the rotor knife trajectory increases. In the solution (Fig. 3b), a

b

c

FIGURE 3. Types of covers used in the examined machines: a – suspended rear cover, b – rear cover with a joint, c – one-piece rotor cover

a rotor of diameter of 560 mm is covered from the top with a fixed cover, and in the rear part – with a suspended cover, consisting of two jointed parts. In this system, as the cover is raised, the distance between the cover and the rotor knife trajectory changes slightly. For the two rototiller models, the change of positioning of the cover is stepless, using an adjustment crank; usually, these machines work as units with additional cultivation shafts. On the other hand, the cover in the model presented by Figure 3c consists of one part, and it is characterized by large curve radius; it covers a rotor of diameter of 480 mm from the rear and from the top, and its position is changed gradually.

In every structural design of the rototiller, the rotor cover should ensure protection against accidental contact with the rotating working knives during normal operation and handling. The safe zone has been assumed to be the horizontal distance between the working knife trajectory and the end of the lower end of the rear part of the cover being not less than specified in the standard.

RESULTS AND DISCUSSION

In a rototiller with a rear cover suspended as in Figure 3a, when raising the lower end of the rear cover for the purpose of adjustment of its position, the horizontal distance between the working knife movement trajectory and the end of the cover increases (Fig. 4).

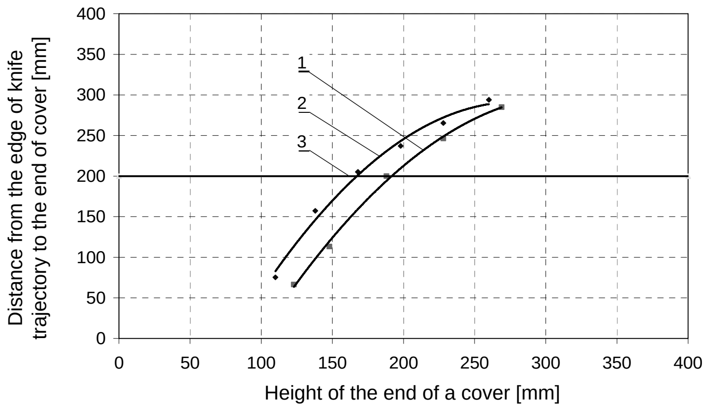

FIGURE 4. The impact of height of the cover on the safety zone in a rototiller with a pivoting rear cover: 1 – fixed to the upper opening, 2 – fixed to the lower opening (elongated), 3 – the required minimum safe distance

When positioning the cover end below 190 mm (curve 1, Fig. 4), the safe distance from the rotor knife movement trajectory, which, according to the requirements, should be at least 200 mm, is not maintained. This is due, among other factors, to the radius of the curve of the cover, its rotation axis and diameter of the rotor. During work, the working knives penetrate the soil; however, in order to meet the requirements, the working depth of the machine should be 190 mm. A more advantageous situation is encountered, when it is possible to lower the rear cover. In such case, the safe distance from the rotor knife trajectory is maintained, when the rototiller is set to the working depth of at least 165 mm. It should be noted that the position of the cover end will change along with longitudinal levelling of the machine for the working depth set, which will change the safe distance from the knife trajectory.

According to Hendrick and Gill [1971], the working depth should be set to make sure that the ratio of the rotor diameter to depth is within the range of 1.1–1.4, at which the rototiller unit work is reduced to a minimum level. Prasad et al. [2014] provide that the working depth exerts significant influence not only on unit work and power demand of the machine, but also the physical properties of the soil layer cultivated. The greater working depth, according to Davis et al. [1982], results in greater soil pulverization. It happens because of the tendency to increase soil recirculation in the machine. The soil pulverization degree is also determined by rotational speed of the rotor, movement speed, number of knives per flange and positioning of the rotor cover [Davis et al. 1982].

In a rototiller with a rear cover suspended as illustrated by Figure 3b, changes in the distance between the working knife trajectory and the end of the cover with regard to adjustment of its positioning are not substantial (Fig. 5). In this case, it is possible thanks to the two-piece structure of the cover with an articulated mechanism. When raising the cover from 100 to 300 mm, the distance from the knife movement trajectory was in each case greater than 200 mm, which was sufficient to maintain the safety zone (Fig. 5).

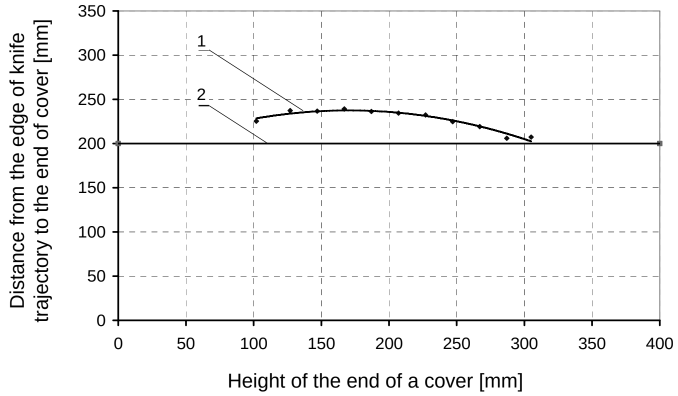

FIGURE 5. Impact of the cover height setting on the safety zone in the rototiller with an articulated rear cover: 1 – cover positioning, 2 – the required minimum safety distance

Positioning of the rotor cover is regulated depending on agrotechnical conditions. The stream of the soil, subjected to the force of impact against the cover, which acts as a barrier that breaks the clods, contributes to its crushing [Davis et al. 1982, Larson et al. 1989]. The effect of impact of the cover is more visible when it is lowered and recirculation of soil clods through the rotor takes place, as it operates like a levelling strip on the soil surface [Culpin 1981, Davis et al. 1982]. Lowering of the cover is required for heavy and dry soils and during work on light soils containing stones, as it is a prerequisite for operational safety.

The level of crushing can be changed to some extent by adjusting the cover position, and of decisive importance here are the soil prosperities – mainly the moisture content [Culpin 1981, Larson et al. 1989]. Therefore, in heavy and moist soils, it may be necessary to raise the cover to prevent clogging of the rotor.

In the structural variant of the rototiller with a single-piece cover, protecting the rotor from the top and from the rear (Fig. 3c), the safe distance between the cover end and the knife movement trajectory is maintained as it is set at the height up to 560 mm (curve 1, Fig. 6). It is important for the machine to be levelled when connected to the tractor. It is possible, when the lower pins of the suspension of the machine are situated in a vertical plane along with the upper

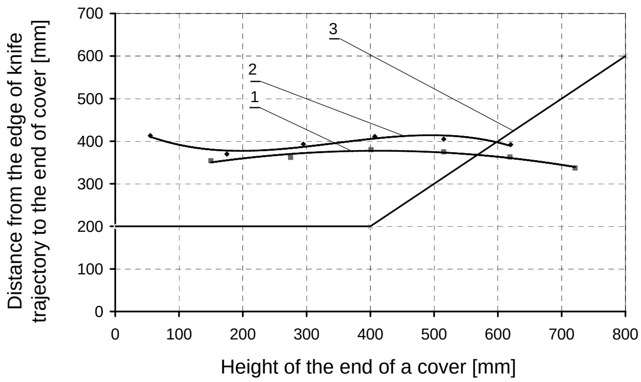

FIGURE 6. The impact of setting of the cover height on the safety zone in the rototiller with a uniform rotor cover: 1 – for the mechanical linkage stand positioned vertically, 2 – for the mechanical linkage stand deflected to the back, 3 – the required minimum safety distance

opening of the mechanical linkage. If the stand of the mechanical linkage system is slightly deflected to the back, in the entire range of setting of the cover end, the safe distance between the cover end and the knife trajectory movement is maintained (curve 2, Fig. 6).

In literature, little has been written on the impact of setting of the rear cover on the quality of work of the rototiller. Bukhari et al. [1996] have examined the impact of setting of the rear cover and movement velocity on the effects of work of the rototiller. Research was conducted only for two positions of the rear cover and three movement speeds. It was stated that soil turning increased, when the rear cover was set higher and when the movement speed was greater. Positioning of the rear cover and the speed of movement also influenced aggregation and break-up of the soil. At a lower speed and in the lower positioning of the rear cover, a large share of small soil aggregates was recorded, as well as establishment of a sowing layer of a very good quality.

In research conducted by Sharda and Singh [2004], under varying field conditions after harvesting of paddy rice and wheat – manually and using a harvester – the rear cover was set in a fully lowered or fully raised position. The greatest reduction of plant remains (99%) was achieved, when the rear cover of the rototiller was lowered, regardless of the type of knife used and the rotor speed applied.

CONCLUSIONS

1. The presented concept for determination of the safety zone between the knife movement trajectory and the rear rotor cover allows for precise establishing of this zone throughout the entire range of positioning of the cover under laboratory conditions.

2. The safety zone between the knife movement trajectory and the rear rotor cover changes along with the positioning of the cover and depends on the possibility of its elongation, working depth and longitudinal levelling of the machine in relation to the tractor.
3. It is more difficult to comply with the safe distance requirements with regard to the distance between the knife movement trajectory and the rear cover of the rotor when the machine is set to small working depth.
4. Use of a two-piece rear cover with an articulated mechanism in a rototiller allows for maintaining of the safety zone regardless of positioning of the cover or the working depth.

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Streszczenie: *Metoda wyznaczania strefy bezpieczeństwa między osłoną a wirnikiem glebogryzarki*. Celem badań było opracowanie analitycznej metody wyznaczania strefy bezpieczeństwa między osłoną tylną a wirnikiem glebogryzarki dla różnych typów osłon. Wykorzystując wielkości i relacje występujące między charakterystycznymi punktami wirnika i osłony maszyny, opracowano algorytm do obliczenia strefy bezpieczeństwa, który ma zastosowanie w całym zakresie ustawienia tylnej osłony i głębokości roboczej. Za strefę bezpieczeństwa przyjęto poziomą odległość końca tylnej osłony wirnika od toru ruchu noży tnących, zgodnie z wymaganiami normy zharmonizowanej EN ISO 4254-5:2009+AC 2011. Do określenia tej odległości konieczne są pomiary: wysokości ustawienia osłony, długości odcinka łączącego oś obrotu wirnika i tylnej krawędzi osłony oraz średnicy wirnika z nożami. Strefę bezpieczeństwa w obszarze tylnej osłony maszyny zweryfikowano na trzech typach glebogryzarek różniących się konstrukcją osłon. Przeprowadzona analiza badań wykazała, że zastosowanie w glebogryzarce dwuczęściowej osłony tylnej z mechanizmem przegubowym pozwala utrzymać wymaganą strefę bezpieczeństwa niezależnie od położenia osłony i głębokości pracy.

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Authors' address:
Michał Sypuła, Jacek Klonowski, Tomasz Nowakowski, Aleksander Lisowski, Jarosław Chlebowski, Adam Strużyk, Adam Świętochowski
Wydział Inżynierii Produkcji SGGW
Katedra Maszyn Rolniczych i Leśnych
02-787 Warszawa, ul. Nowoursynowska 164
Poland
e-mail: michal_sypula@sggw.pl