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Transverse Movement Kinetics of a Unit for Inter-Row Crops—Case Study: Cultivator Unit

Pavol Findura [1], Volodymyr Nadykto [2], Volodymyr Kyurchev [2] and Łukasz Gierz [3,*]

[1] Institute of Agricultural Engineering, Transport and Bioenergetics, Faculty of Engineering, Slovak University of Agriculture in Nitra, 949 76 Nitra, Slovakia; pavol.findura@uniag.sk
[2] Mechanical and Technological Faculty, Dmytro Motornyi Tavria State Agrotechnological University, 72312 Melitopol, Ukraine; volodymyr.nadykto@tsatu.edu.ua (V.N.); volodymyr.kyurchev@tsatu.edu.ua (V.K.)
[3] Institute of Machine Design, Faculty of Mechanical Engineering, Poznań University of Technology, ul. Piotrowo 3, 60-965 Poznań, Poland
* Correspondence: lukasz.gierz@put.poznan.pl; Tel.: +48-782169798

Abstract: Due to the negative impact of chemical inter-row weed control on the environment, mechanical weed control is increasingly used in practice. Machine-tractor units (MTU) are used with the row cultivator's rear and frontal central position for its implementation. We have designed a unit in which side cultivators are used along with the central one. This paper considers the transverse movement kinematics of such an MTU's outside right and left cultivators' working devices in the horizontal plane. The present emulation of side machines is made by changing the longitudinal coordinate of their location relative to the tractor's front and rear axles. Calculations have established that the frontal cultivator responds more intensively to the control action by changing the turning angle of the tractor's steering wheels. However, if the value of this parameter is less than 2.75°, a rear-mounted cultivator is preferred, because in this case, the values of lateral deviations for the external, left, and right working device are smaller. When the turning angle of tractor wheels is from 1° to 3° (typical for MTU row work), a threefold increase in the working width of the cultivator causes a slight antiphase deviation in its external working devices (an increase or decrease in the amplitude of these deviations does not exceed 4%). The model that we have developed allows us to select the values of the MTU design parameters for which the lateral displacement will be very small (close to zero). As the turning angle of the tractor wheels increases to 3°, the external left and right working devices of the cultivators react inversely. This means that in the case of the rear machine, the values of lateral displacements increase, while in the case of the front machine, they decrease. At a turning angle of the tires of the tractor wheels close to 2.5°, the lateral displacements for the rear and front machines are the same.

Keywords: row cultivator; working devices; turning angle of tractor wheels; yaw angle

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1. Introduction

One of the most essential and responsible agricultural technological operations is the inter-row cultivation of row crops. Its application aims to solve several problems: (I) weed control; (II) reduce soil moisture loss by destroying its capillary structure in the capillary structure of the upper layer capillary structure; (III) aeration of the soil root layer.

Weeds steal nutrients, water, and sunlight, reducing both the quality and the quantity of crop yields [1]. Taking up the necessary space from weeds can make crop plants more susceptible to diseases and even pests [2,3]. Previous research shows that a lack of weed control can cause up to 90% crop loss [4,5]. The most commonly used weed control methods include chemical, mechanical, and a combination of these two methods [4]. In many countries, chemical control using herbicides dominates, increasing production costs and negatively affecting the natural environment [6]. At the same time, herbicide residues in soil negatively affect the quality [7], as well as of drinking water [8], and have a harmful effect on soil microorganisms [9]. According to the resolutions of the European Green Deal on crops by 2030, we are to strive to reduce the use of chemically synthesized plant protection products by 50%. Therefore, there is a visible need to develop alternative methods of weed control that retain moisture in the soil and aerate it. There are known non-chemical methods for weed control, e.g., intercropping, flaming, or steaming, but these methods are not economically justified [10]. Furthermore, thermal methods of weed control are very expensive (energy-consuming) and inefficient [11,12].

Taking into account the care of the natural environment and the requirements of the modern market for healthy food [13], the development of mechanical weed control methods is also becoming increasingly important in conventional agricultural systems [14,15].

It should be emphasized once again that chemical control does not retain moisture in the soil (does not reduce moisture loss) and does not create conditions for increasing the aeration of the root layer.

Although inter-row cultivation can solve all three problems, practical implementation requires determining the best parameters. One of the important parameters is the ability to reduce or even completely eliminate damage to crop plants, even if the rows in the crops are not perfectly straight. To systematize the boundary conditions of inter-row cultivation, many countries have developed agrotechnical requirements with respect to the straightness of sowing (planting) of crops.

In Ukraine, for example, the crop trajectory is acceptable if the variance of its amplitude oscillations does not exceed 12.5 cm^2, and in frequency, most of them (at least 95%) are in the range of 0–25 m^{-1} [16].

On the other hand, the mechanical control of processing inter-row spacing of crops raises requirements for the technical devices used for its implementation. If this unit consists of a tractor and a cultivator, the tractor's tires must fit into the row crops' inter-row width. With relatively narrow row spacings (45 cm, for example), the tractor should be equipped with double tires and the ballast (if necessary) of its front axle should be carried out [17], taking into account the requirements of "ecophilic" tires. Special devices are required to design an asymmetric machine-tractor unit in the case of the tractor track with a width ratio in the form of an odd number [18].

Most inter-row units consist of a self-propelled vehicle and rear-hitched cultivator(s). Units with rear-driven machines have different designs and their own set of work devices [19–22]. Recently, robotic machines have been used more and more frequently [23], which are characterized by good efficiency despite small operating widths and save time for the operator because they do not require its participation during agrotechnical procedures.

Sometimes, row crops in inter-row zones are cultivated with units with a front-mounted cultivator [24,25]. But, like many rear-row tillers, they have relatively small operating widths and are often used at relatively low operating speeds [26,27].

As part of preliminary research, we developed unit variants for inter-row treatments in which row cultivators can be placed on the back, front, and sides (left and right) [28]. Such units can have an operating width of up to 16.8 m. However, there is still no sufficient justification for designing units for inter-row treatments. There are also no data on setting the most favorable technical parameters. Therefore, theoretical considerations of the kinematics of movement of inter-row cultivation units with a large operating width in the horizontal plane were undertaken. At the same time, note that the theoretical approaches used earlier to solve this problem were not inappropriate. This is because previously the lateral shift of the cultivator relative to the agricultural tractor was not considered. Moreover, analysis of the kinematics of movement of inter-row cultivation units requires taking into account the deflection angles of the tractor's front tires depending on the steering angle of the entire unit.

In most cases, a row crop cultivator is attached to a tractor without the possibility of mutual rotation in the horizontal plane. However, as the operating width of the row crop units increases, the momentum generated increases. The total torque of the cultivator results from the unequal working resistances of individual sections of the cultivator over its entire operating width. As a result, its rigid connection to the tractor may negatively affect the straightness of the MTU's movement along the crop rows. The consequence may be reduced stability of the width of the protection zone and even the possibility of mechanical damage to cultivated plants. It should be emphasized once again that the scientific and information community has not found any theoretical considerations or research results that would solve this problem.

Due to the above, this article aims to present the results of theoretical and experimental research on the kinematics of inter-row movement of the machine-tractor unit (MTU) to justify its scheme and design parameters, taking into account the following: (I) the operating width of the MTU; (II) the coordinates of the longitudinal position of the working devices of row cultivators; (III) the deflection angle of the tractor tires at the steering angle of its front steering wheels; (IV) the method of connecting the row cultivator to the tractor in the horizontal plane: variant (A) rigid and variant (B) articulated.

2. Material and Methods

This chapter includes three sections. The first of them briefly outlines the theory of the transverse displacement of the front- and rear-mounted cultivators in the horizontal plane during static turning of the machine-tractor unit. The second section outlines the methodology for field research of a unit for processing sunflower rows with a rigid and articulated connection of the cultivator to the tractor. The third section describes the methods for statistical processing of the obtained data.

2.1. Theoretical Premises

To solve the problem mentioned above, a machine-tractor unit was considered, consisting of a tractor with front steering wheels, as well as rear and front row cultivators of the same operating width B_p (Figure 1). Such a conditional kinematic diagram is quite suitable for theoretical studies, considering cultivators' separate and combined use as part of a row MTU. This is even more convenient when considering options for their placement on the sides of the mobile vehicle by setting the appropriate values for the l_z (distance between the tractor's rear axle and the rear cultivator's working devices) and l_p (distance between the tractor's front axle and the front cultivator's working devices) (see Figure 1).

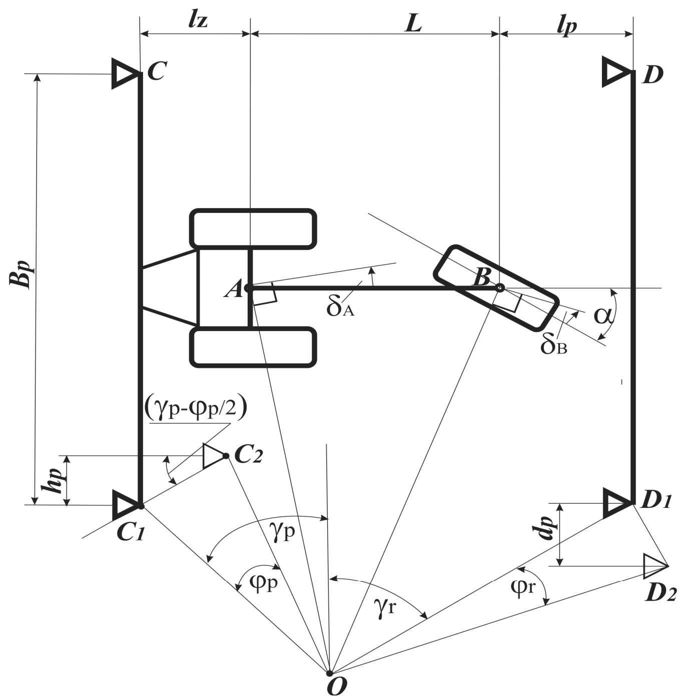


Figure 1. Row MTU kinematic diagram.

Let us assume that the tractor deviates from the rectilinear motion under random perturbing factors that arise during the inter-row MTU operation. In each case, its subsequent movement along a curvilinear trajectory will continue until the tractor driver begins to restore the specified direction of movement.

Next, we will study the factors that affect the lateral displacements of the hitched machines' working devices during the tractor's curvilinear movement and derive formulas for calculating the magnitude of these displacements.

Let the front wheels in the MTU movement deviate by angle α (Figure 1). As practice shows, with inter-row cultivation of row crops, the value of this angle does not exceed 3°. In this case, the tractor will move along a particular curve. Its center (point O, Figure 1) is located at the intersection point of the geometric axes of the front and rear wheels of the tractor, considering their yaw angles δ_B and δ_A, respectively. Each of them is the angle between the plane of the wheel and the proper direction of its rolling.

Initially, the outside working devices of the rear machine are in positions C and C_1, and the front ones are in positions D and D_1. Here, C and C_1 are the placement points of the outside left and outside right working devices of the rear mounted cultivator, and D and D_1 are the placement points of the front-mounted machine's outside left and outside right working devices of the front-mounted machine.

Note that both machines are attached to the tractor without the possibility of mutual turning relative to each other in the horizontal plane. As a result, the tractor's steering wheels are turned at an angle α (see Figure 1), and the outside right working devices of the rear machine will turn by some angle φ_p, moving from position C_1 to position C_2 (see Figure 1). The measure of their transverse displacement is the distance h_p.

A similar result of turning the outer right working devices of the frontal machine at an angle φ_r will be their transverse movement from position D_1 to position D_2 by a distance d_p. It should be noted that similar transverse movements of the leftmost working devices of both machines at distances h_o and d_o in Figure 1 are not displayed.

The equations for determining the lateral displacements hp and dp of working devices (using the example of a cultivator) were derived in the computer algebra application MathCad by Mathcoft, Cambridge, MA, USA, whose functionality is similar to the Mthematica application. The final form of the derived equations takes the form shown in (1)–(4):

- For the rear hitch machine:

$$h_p, h_0 = \left(\varphi_p - 2\cot\gamma_p \cdot \sin^2\frac{\varphi_p}{2}\right)\cdot\left(l_z + \frac{L\cdot\delta_A}{\delta_A + \alpha - \delta_B}\right); \quad (1)$$

$$\cot\gamma_p = \frac{L \pm 0.5B_p\cdot(\delta_A + \alpha - \delta_B)}{l_z\cdot(\delta_A + \alpha - \delta_B) + L\cdot\delta_A}; \quad (2)$$

- For the frontal machine:

$$d_p, d_o = \left(\varphi_r + 2\cot\gamma_r \cdot \sin^2\frac{\varphi_r}{2}\right)\cdot\left(L + l_p - \frac{L\cdot\delta_A}{\delta_A + \alpha - \delta_B}\right); \quad (3)$$

$$\cot\gamma_r = \frac{L \pm 0.5B_p\cdot(\delta_A + \alpha - \delta_B)}{\left(L + l_p\right)\cdot(\delta_A + \alpha - \delta_B) - L\cdot\delta_A}. \quad (4)$$

where:

B_p—operating width of the machine (cultivator) (m);
L—wheelbase of an agricultural tractor (m);
l_z—distance of the cultivator from the rear axle of the tractor (m);
l_p—distance of the cultivator from the front axle of the tractor (m);
α—turning angle of tractor wheels (deg);
γ_p—deviation angle of the rear cultivator's outside working parts from the vertical (deg);

γ_r—deviation angle of the front cultivator's outside working parts of the front cultivator from the vertical (deg);
δ_A—yaw angle of tractor rear wheel tires (deg);
δ_B—yaw angle of tractor front wheel tires (deg);
φ_r—turning angle of the front machine (front cultivator) (deg);
φ_p—turning angle of the rear machine (rear cultivator) (deg);
C, C_1—starting points from the rear machine (rear cultivator);
C_2—points of relocation of the rear machine (cultivator in the rear);
D_2—relocation points of the front machine (cultivator in front);
D, D_1—starting points from the front machine (front cultivator);
d_p—move point D_1 to position D_2 (m);
h_p—move point C_1 to position C_2 (m);
h_0—displacement of the right outside working parts of the rear cultivator after turning it (m);
d_0—displacement of the right external working parts of the front cultivator after turning it (m).

The "+" sign in the numerators of Equations (2) and (4) after the wheelbase L refers to the left exterior, and the „$-$„ sign refers to the outside right exterior working devices of the machine's outside right exterior.

2.2. Experimental Studies

Based on the analysis of Figure 1, it is evident that φ_p and φ_r angles are functions of the the turning angle of tractor wheels (α). That is, $\varphi_p = k_1 \cdot \alpha$ and $\varphi_r = k_2 \cdot \alpha$, where k_1 and k_2 are some coefficients of proportionality. In this study, $k_1 = k_2 = 0.5$ was taken. The angle value α in the calculations was changed within 1–6°. In this case, as shown by preliminary studies of the unit as part of the KhTZ-16131 tractor (Kharkiv, Ukraine) and the KRNV-8.4 row cultivator (Elvotri, Ukraine) with B_p = 8.4 m, the actual values of the coefficients k_1 and k_2 are quite close to the accepted ones. The values of the remaining parameters included in Equations (1)–(4) were as follows: L = 2.86 m; δ_A = 1–3°; δ_B = 1–3°; $l_z = -2$; 0; 2 m; $l_p = -2$; 0; 2 m.

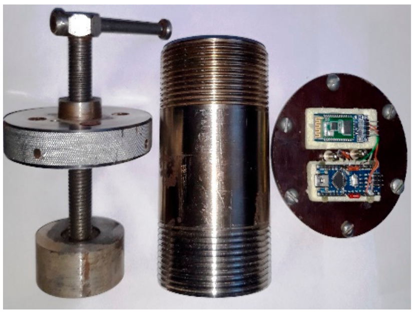
The physical object of the research was an MTU consisting of a KhTZ-16131 tractor and a KRNV-8.4 row-crop cultivator (Table 1). This MTU was configured according to two diagrams: (1) rigid attachment of the cultivator with the tractor in the horizontal plane (variant A) and articulated attachment (variant B). In the unit of variant A, the check chains (1) of the tractor's three-point hitch linkage were tensioned, and in variant B, they were freely slack. This allowed the cultivator with the low-linkage hitch (2) to turn relative to the tractor in a horizontal plane.

Table 1. Technical characteristics of weeding machine-tractor unit.

Index	Value
Tractor weight (kg)	8200
Cultivator weight (kg)	1920
Cultivator number sections	13
Distance between cultivator sections (m)	0.7
Cultivator operating width (m)	8.4
Tractor wheelbase (mm)	2860
Tractor track (B_t, mm)	2100
Tractor tires	16.9R38

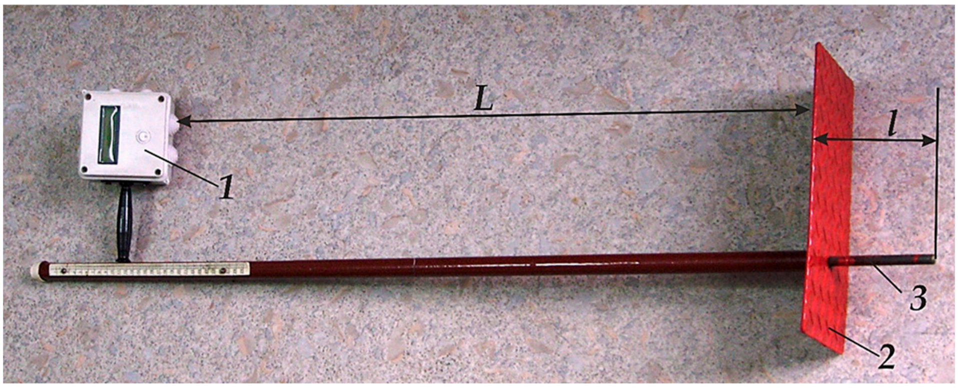
The machine-tractor team from both schemes worked in the same agricultural field during the inter-row weeding of sunflower seeds. During the experimental studies, we measured (a) soil moisture and density in a layer of 0–10 cm; (b) the depth of tillage between rows; (c) the width of a one-sided protective zone; (d) the row-crop unit's movement velocity.

To measure soil moisture, we used a specially developed device (Figure 2a). Its operation is based on the dielectric constant, which depends on its moisture. A piston is mounted on the top cover of the device. It is designed to compact the soil. As a result, the effect of its density on humidity is neutralized. The electronic part is located on the bottom cover of the device. During the measurement process, a dose of soil is placed in the instrument glass. After the piston compacts, its humidity (%) is recorded on the electronic part. The measurement error of this device does not exceed 1%.



(**a**)

(**b**)



(**c**)

Figure 2. Devices for measuring humidity (**a**), density (**b**), and tillage depth (**c**): 1—Arduino Uno; 2—support; 3—measuring probe.

Soil density was measured using a device developed by us in the form of a cylinder with a volume of 28.35 cm^3 (Figure 2b). The soil sample taken with a cylinder was weighed on a scale (EGY-100, Dneproves, Dnipro, Ukraine) set to measure in ounces (oz). Because 1 oz = 28.35 g, the EGY-100 scale displayed the soil mass, corresponding to its density in $g \cdot cm^{-3}$. The measurement error with this device does not exceed 0.01 $g \cdot cm^{-3}$. The measurement of soil density and moisture was carried out along the diagonal of the field. The measurements for each parameter were 30, and the measurement step was 5 m.

We used a device (Figure 2c) based on Arduino Uno (Milan, Italy) to measure the depth of sunflower inter-row cultivation. This device uses an ultrasonic sensor US-025 (Guangdong, China), whose measurement error does not exceed 3 mm. During measurement, the device is installed with a support (2) in the processed background. The measuring probe (3) is lowered to the tillage depth l. Arduino Uno (1) measures the L_a distance. Then, according to the algorithm built into the Arduino UNO program (1), the distance L_a was converted as a function of the cultivation depth $L_a = f(l)$. The value of the measurement distance L_a and the cultivation depth l are displayed on the built-in screen of this measuring device. Cultivation depth measurements were made in two repetitions at 200 measurement points with a step of 0.2 m.

For the purposes of the experiment, a Ukrainian sunflower hybrid of the LOGOS variety (for the parameters, see Table 2) from a seed farm located near the city of Melitopol, Ukraine, was used.

Table 2. Logos hybrid characteristics.

Index	Value
Reproduction	F-1
Variety purity (%)	99.8
Germination (%)	94
Humidity (%)	6.5
Thousand kernel weight (g)	78.2
Seed dressing	Apron XL

The height of the sunflower seedlings was determined along the longest diagonal of the field using a ruler with a measurement error of ±0.05 cm. This method is used by the Polish State Forests and the Chamber of Agriculture in Poland and has been validated when measuring and estimating forest and agricultural damage. Approximately 300 measurements were planned to be made with a measurement step of 1 m.

The width of the protective zone of plants in sunflower rows was determined in three repetitions using a caliper with a measurement error of ±0.5 cm. The number of such measurements in each row, performed in steps of 1 m, was at least 250. On the basis of these measurements, the average width of the protection zone and other statistical parameters, including standard deviation or mean error, were calculated.

The time (t_a) for the unit to pass the test field set with a length of L_a = 250 m was recorded using an electronic HS-8200, Annadue (Guangdong, China), stopwatch with a measurement accuracy of up to 0.1 s. The unit movement velocity (V_a) was calculated using the following Formula (5):

$$V_a = \frac{L_a}{t_a}; \tag{5}$$

The measurement error of this parameter does not exceed 0.01 m·s^{-1}.

2.3. Statistical Analysis

The measurement results were subjected to statistical analysis. The null hypothesis of equality/inequality of the compared variances D at a statistical significance level of 0.05 was tested using the well-known Fisher F-test.

Based on the measurements of the width of the protective zone on one side, the following was calculated: the mean value, the error of the sample mean, the least significant difference (at a statistical significance level of 0.05) for the compared mean values, the standard deviation, the variance and its error, the coefficient of variation, and the normalized spectral density.

We used a program to calculate the normalized spectral density of oscillations in the width of the protective zone, which we developed in the Mathcad 15.0 environment. Statistical characteristics (except for the variance error) were calculated using the Analysis Toolpak program (Descriptive Statistics-Microsoft Excel, Version 2208). The variance error (D_{er}) was calculated using the following Formula (6):

$$D_{er} = \sqrt{\frac{2 \cdot D^2}{n-1}}, \tag{6}$$

where D is the variance in fluctuations in the protective zone of the width of the sunflower plants (cm^2); n is the width of the measurement number of the protective zone.

3. Results and Discussion

3.1. Theoretical Study of the Row-Crop Cultivators' Turn Kinematics

The influence of the rear and front cultivators' operating width (B_p) on the deviation of their outside right (h_p, d_p) and left (h_o, d_o) working bodies are shown in Figure 3. The B_p parameter was set to 5.6, 8.4, 11.2, and 16.8 m. The values of the other parameters, included in Equations (1)–(4), were constant and equal: α = 3°; $\delta_A = \delta_B = 2°$; $l_p = l_z = 2$ m.

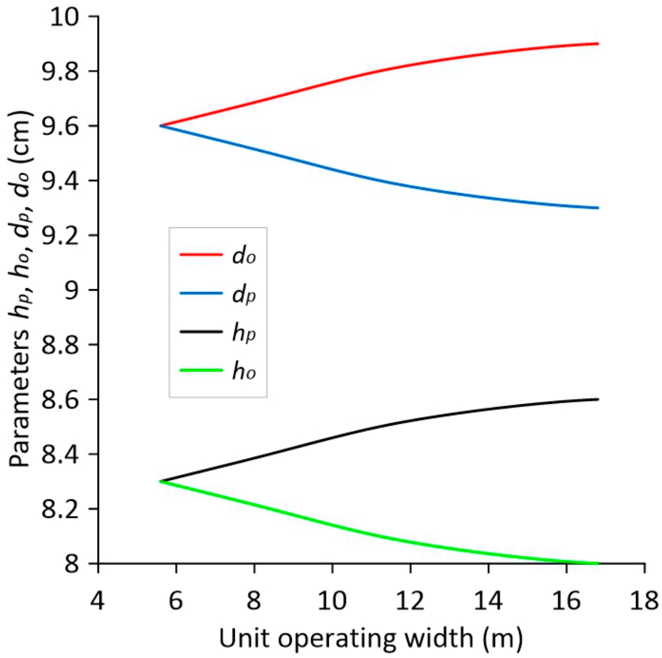


Figure 3. The dependence of the transverse displacements of the row cultivator working devices from its operating width.

Calculations have established that with an increase in the rear row cultivator operating width and a change in the unit movement with the tractor's steering wheels' turning angle from 1° to 3°, the transverse deviation of its outside right working devices tends to increase qualitatively (see Figure 3). In quantitative terms, this increase is insignificant: with an increase in the B_p value by a factor of three (from 5.6 to 16.8 m), the value of the h_p parameter increased by only 3.6%. The deviations of the outside left working devices of the rear cultivator decreased by the same 3.6% (curve h_o, Figure 3).

The opposite trend is observed in the behavior of the frontal cultivator's outside working devices. That is, with an increase in the cultivator operating width by three times, the transverse deviations of the outside left working devices (d_o curve, Figure 3) increase by 3.1%, and the deviations of the outside right ones (d_p curve, Figure 3) decrease by the same amount.

Based on the obtained research results, it can be noted that for small values of the turning angle of tractor wheels (which is typical for MTU row work), increasing the cultivator's width by three times causes small antiphase deviations (an increase or decrease in the amplitude of lateral deviations does not exceed 4%).

The change in the value of the tractor's steering wheels' turning angle is qualitatively the same, but quantitatively, it has a different effect on the changing nature of the cultivator's working devices' transverse deviations. Their values in both variants of aggregating the row cultivator with the tractor increase as the values of the α parameter increase (Figure 4). But the dynamics of these processes is different. The frontal cultivator reacts more intensively to changes in the α parameter. Furthermore, when the value of the turning angle of tractor wheels is less than 2.75°, it is generally preferable because in this case, the deviations of its working devices (d_p, d_o) are less than those of a rear-hitched cultivator (h_p, h_o).

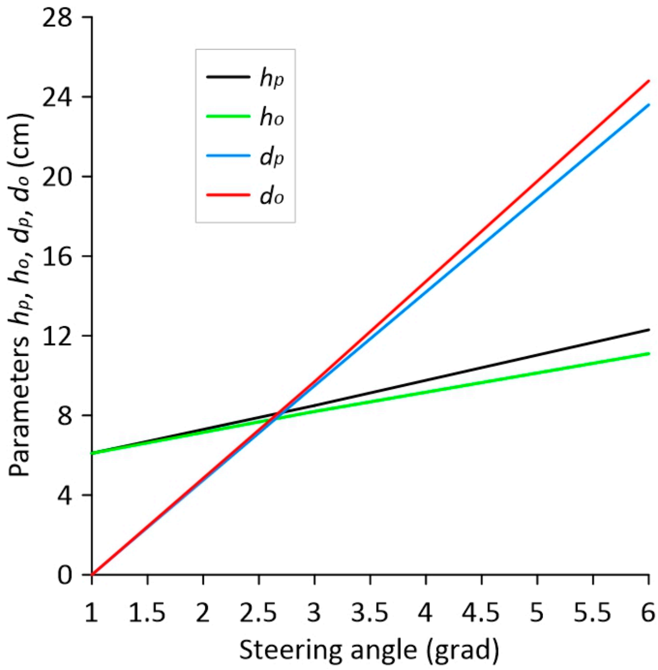


Figure 4. Dependence of the transverse displacements of the workhorse plant of the tractor's steering wheels' turning angle.

During widespread GPS introduction, which guarantees fluctuations in the tractor's steering wheels' turning angle from 1° to 2°, considering this factor in choosing a row-crop MTU diagram can be decisive. As noted above, the lateral arrangement of row cultivators relative to the tractor can be emulated by changing the values of the l_p and l_z parameters (see Figure 1). Analysis of dependences (1) and (2) shows that an increase in the value of the l_z parameter, equivalent to the distance of the rear cultivator from the tractor, increases the transverse displacements of its outside right and left working bodies (Figure 5).

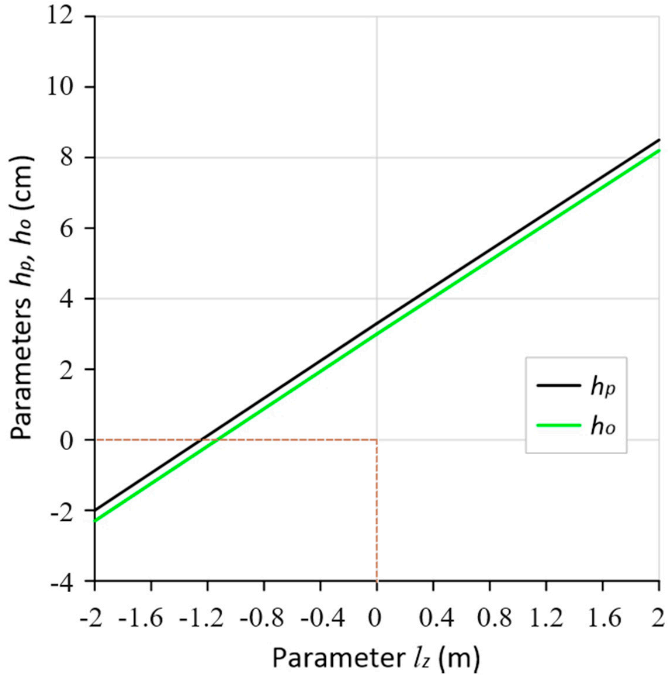


Figure 5. Dependence of transverse displacements of the working devices of the rear-hitched row cultivator from the coordinate of its placement relative to the tractor.

However, when the sections of the row cultivator are moved forward relative to the rear axle by a distance $l_z \approx -1.2$ m, we reach the zone of absence of their transverse displacements (h_p, $h_o \approx 0$). Such a result, in principle, is ideal.

Similar reasoning is valid for the front row cultivator (Figure 6). For this, under the conditions $\alpha = 3^\circ$, $\delta_A = \delta_B = 2^\circ$, and $B_p = 8.4$ m, zero displacement of the outside working devices can be achieved at $l_p \approx -0.8$ m. This can be achieved by shifting the sections of the front cultivator back by a specified distance with respect to the axis of the tractor's front wheels.

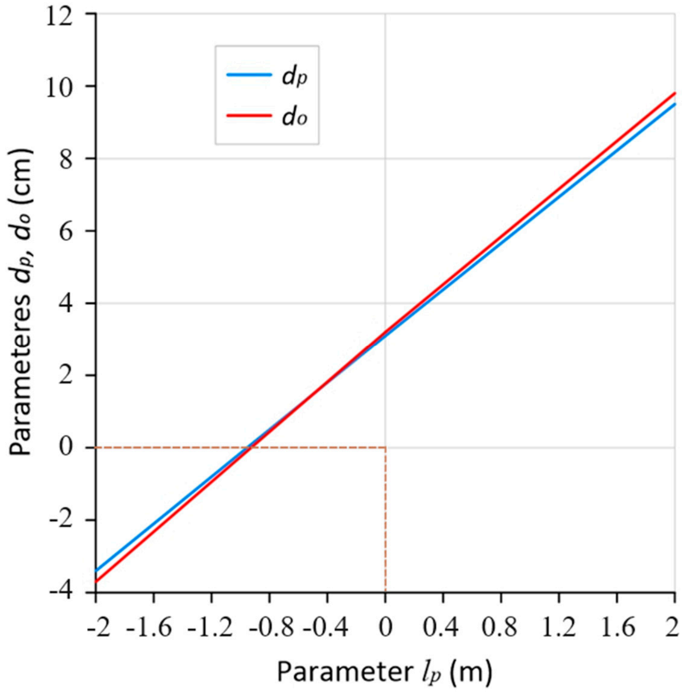


Figure 6. Dependence of transverse displacements of the working devices of the front-hitched row cultivator from the coordinate of its placement relative to the tractor.

As a result, we find that, taking into account the specific values of the row-crop MTU design parameters included in Equations (1) and (2), it is possible to choose such an arrangement of the inter-row cultivator working devices, at which their transverse displacement will be close to zero. With the lateral placement of the cultivators as part of a row-crop MTU, the central machine can be placed behind and in front of the tractor. Based on the data analysis in Figure 4, a frontal cultivator is preferable when the tractor's steering wheels' turning angle is increased up to 3°.

The theoretical analysis shows that with an increase in the δ_A parameter from 1 to 3°, the outside left and right working devices of cultivators react oppositely. Namely, if the values of h_p and h_o transverse displacements increase for the rear machine, then the values of similar d_p and d_o displacements decrease for the front cultivator (Figure 7).

At the yaw angle of the tractor's steering wheels' tires $\delta_A \approx 2.5^\circ$, there is an approximate equality of the indicated transverse displacements, i.e., $h_p \approx h_o \approx d_p \approx d_o$. This provision means that with a turning angle of the tractor wheels $< 2.5^\circ$, the difference in the lateral deflections of the external right and external left working devices of the cultivator is so small that it can be neglected.

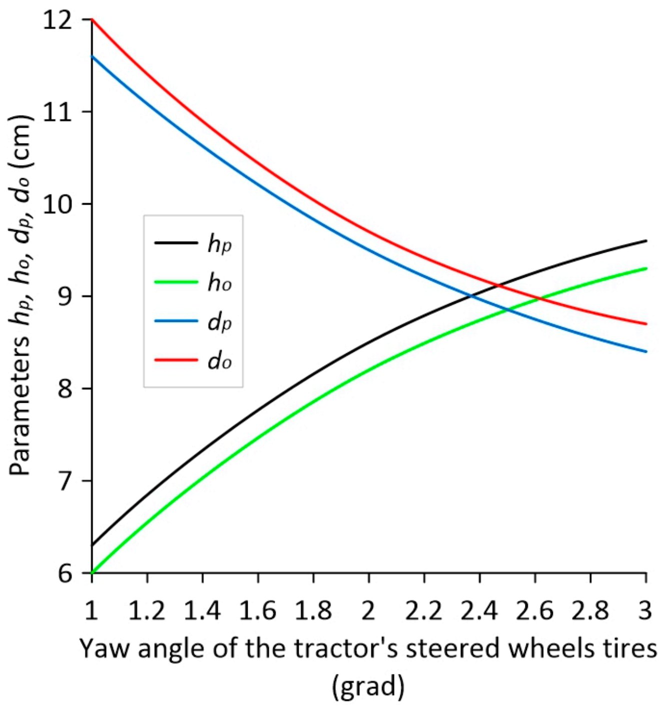


Figure 7. Dependence of the transverse displacements of the working devices of the row cultivator from the tractor's steering wheels' tires' yaw angle.

The algorithm for further use of the δ_A parameter set value can be as follows. Considering the dynamic of MTU movement of the row in the horizontal plane, it is possible to determine the lateral force (T_B) acting on the tractor's steering wheels. The product $\delta_A \cdot T_B$ gives the value of the tire yaw resistance coefficient (k_B). After determining this parameter, guided by the methodology described by [29], it is possible to calculate the required air pressure on the tires of the steering wheels of the tractor. Similarly, you can carry out this step when determining the tires of the air pressure in the rear wheels.

From the above, using only a centrally located cultivator or its combination with side ones can provide four different row-crop MTU diagrams (Figure 8).

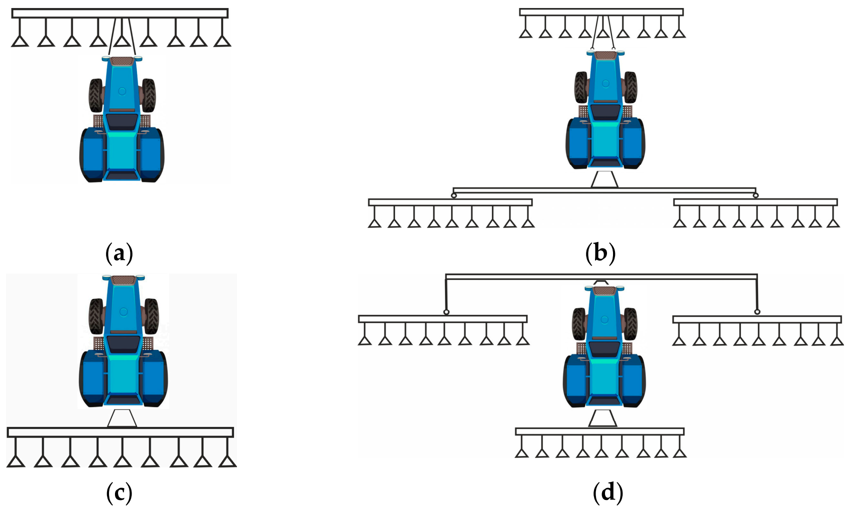


Figure 8. Row MTU design variants: (**a**) a cultivator mounted at the front, (**b**) a cultivator mounted at the front and two cultivators at the rear, (**c**) a cultivator mounted at the rear, and (**d**) two cultivators mounted at the front and one at the rear.

In general, the operating width of the side (B_{po}) and central (B_{pc}) cultivators may not be the same. The following equation describes the ratio of these parameters:

$$B_{po} = k \cdot B_{pc},$$

where k is the proportionality coefficient, $0 < k \leq 1$. In the MTU design of the row described, for example, in [17], the coefficient k is 0.25.

3.2. Results of Experimental Studies of Row-Crop MTU

To enrich the theoretical considerations, experimental research was also carried out. During these tests, a row unit was used according to the diagram in Figure 8c in two variants: variant A, a cultivator rigidly connected to the tractor, and variant B, a cultivator articulately attached to the tractor.

Moreover, all of the results obtained are valid for other diagrams. The conditions for conducting field research are described in Table 3.

Table 3. Conditions for inter-row crop culture of sunflower.

Index	Value
Recommended protective zone (cm)	10.0
Soil cultivation depth (cm)	8.1 ± 0.3
Mean height of sunflower plants (cm)	18.4 ± 1.1
Soil humidity (%)	15.9
Soil bulk density ($g \cdot cm^{-3}$)	1.25
Weed density ($g \cdot m^{-2}$)	79.6

During the inter-row processing of sunflower rows (Figure 9), the unit moved at a velocity whose mean value was 2.2 $m \cdot s^{-1}$.

Figure 9. Culturing unit at work.

When the cultivator was rigidly attached to the tractor (variant A), the width of the protective zone of the mean value of the sunflower rows was 10.1 cm (Table 4).

The value of the same parameter for the unit with the articulated attachment of the cultivator (variant B) was equal to 8.9 cm. At the statistical significance level of 0.05, the resulting difference of 1.2 cm is significant, as it is significantly greater than LSD_{05}, equal to 0.3 cm (Table 4). Thus, the null hypothesis about the equality of mean values is rejected. The established one-sided value of the width of the protective zone for sunflower plants is 10.0 cm (Table 3). It follows that when the unit operates according to variant A, the specified zone is practically not disturbed. In the case of using the unit according to variant B, the width of the protective zone is reduced by 1.1 cm^2.

Table 4. Statistical characteristics of sunflower protection zone width.

Index	Value	
Cultivator Joining Variant	**Rigid (A)**	**Articulated (B)**
Mean protective zone (cm)	10.1	8.9
Mean error (cm)	0.09	0.10
Mean LSD_{05} (cm)	0.3	
Standard deviation (σ, ±cm)	1.12	1.26
Variance (cm^2)	1.25	1.58
Variance error (cm^2)	0.15	0.18
Coefficient of variation (%)	11.1	14.1

The oscillation variances in this parameter are arithmetically different (see Table 4). But this difference (0.33 cm^2) is statistically insignificant and therefore random. The proof of this is the actual F-test value, which is 1.26. This is less than the table value of 1.39 at a statistical significance level of 0.05. Moreover, the error ranges of the sample values of the compared variances practically overlap (Figure 10). This is more proof that at least at a statistical significance level of 0.05, the null hypothesis about the equality of the compared variances of oscillations in the width of the protective zone is not rejected. That is, both sample variances represent the same general population.

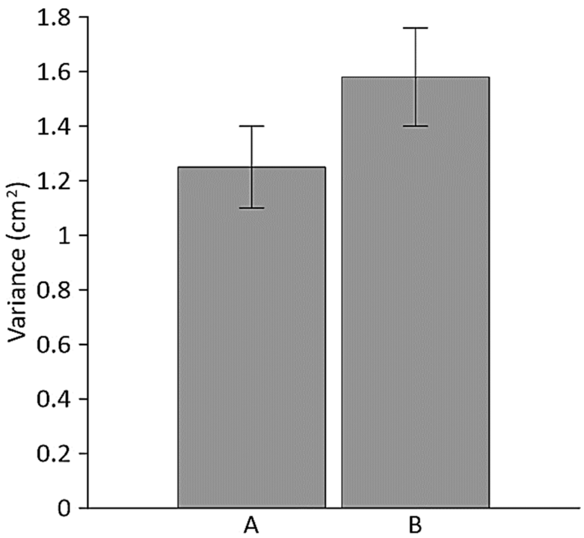


Figure 10. Variances of oscillations in the width of the protective zone with rigid (A) and articulated (B) variants for attaching the cultivator to the tractor.

While variance evaluates the energy of the oscillation process, spectral density allows us to assess its internal nature, namely, frequency. As the analysis of the obtained data showed, for the unit according to variant A, the main part of the oscillation variance in the random process under consideration is concentrated in a narrower frequency range: 0–0.6 m^{-1} (Figure 11). At a unit velocity of 2.2 $m \cdot s^{-1}$, this is 0–1.32 s or 0.2 Hz. The maximum value of the normalized spectral density occurs at a frequency close to zero.

At the same time, the main spectrum of the variance in fluctuations in the value of the protective zone width for the option according to variant B is concentrated in a wider frequency range equal to 0–1.2 m^{-1}. For variant A, the range is 0–2.64 s or 0.4 Hz above the unit velocity. The maximum value of the spectral density is shifted toward higher frequencies (Figure 11).

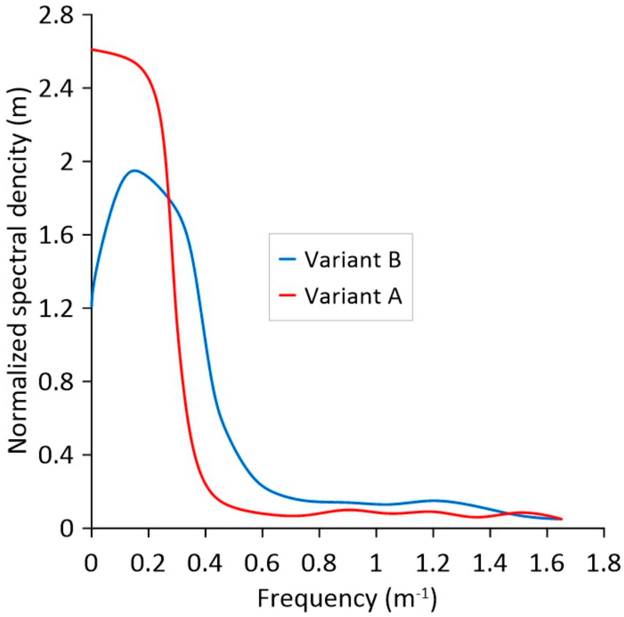


Figure 11. Normalized spectral densities of oscillations in the width of the protective zone for rigid (A) and articulated (B) variants to attach the cultivator to the tractor.

This analysis shows that to ensure greater stability of the width of the protection zone of row plants, it is preferable to rigidly attach the cultivator to the tractor in the horizontal plane. Field experiments with speeds of 1.9 m·s^{-1} and 2.4 m·s^{-1} also confirmed this [7].

Some studies of the rigid connection of the machine with the tractor and the influence of play in the three-point suspension system are indicated in the work of Collians [30] and Hujo [31], but these works did not analyze the deviation of the unit guidance in the inter-row spaces. It should be emphasized that the control of mechanical weeds positively impacts the natural environment [32].

The use of mechanical weed control is consistent with the demands of the European program "European Green Deal" [33,34], which has recently been of invaluable importance to consumers of agricultural produce.

4. Conclusions

This article presents the influence of the design parameters (in particular, the rigid or articulated connection) of the inter-row cultivation unit on the lateral displacement of machines suspended on the tractor at the rear or front during static turns using the example of cultivators. The lateral shift of the cultivator in the horizontal plane was determined by the width of the protection zone during inter-row cultivation in the example of sunflower.

The analysis of the test results showed that the front cultivator responds more intensively to changes in the rotation angle of the tractor's steering wheels (α) than the rear cultivator. For values of the angle (α) of rotation of the steering wheels less than 2.75°, it is recommended to hang the cultivator on the rear, because the values of lateral deviations on the left and right sides of the working device are smaller. For the steering angle of the tractor's steering wheels from 1° to 3° (typical for inter-row MTU work), increasing the cultivator's working width by a factor of three increases the antiphase deviation of its working width. At the same time, the increase/decrease in the amplitude of these deviations does not exceed 4%.

The model that we have developed, presented in Equations (1)–(4), is universal. It can be used for various inter-row crops for the selected working width of the unit. This model can be used in all variants indicated in Figure 8. It indicates the lateral deviations of the unit, and therefore, it can be used with different working widths.

The mathematical relationship allows for the selection of design parameters under such conditions that the lateral deviation of the unit will be very small (practically close to zero).

As the steering angle of the agricultural tractor's steering wheels increases to 3°, the working width deviations increase for the rear-mounted machine, while for the front-mounted machine, these deviations decrease. For a steering wheel rotation angle (α) close to 2.5°, the deviations in the machines mounted in the rear and front are equal. Based on theoretical considerations and experimental tests, it should be concluded that rigid attachment of the machine to the tractor ensures greater stability of the width of the plant protection zone in the rows.

This is confirmed by the calculated average value of lateral deviations, which does not exceed the indicated standards, as well as the calculated oscillation variance (for a rigid connection in the frequency range of 0–2 Hz; for an articulated connection in the frequency range of 0–4 Hz).

In the next steps, we will plan research taking into account the dynamics of horizontal movement of various variants of inter-row aggregates. Particularly noteworthy are the 8b and 8d variants with a large working width, which increase efficiency. In the future, we would also like to investigate the influence of different sowing methods on the variations in inter-row width. The stability of the width between the rows facilitates inter-row cultivation, which is becoming more and more popular when pro-ecological methods of cultivation are recommended, especially when combating weeds.

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