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Experimental research into the effect of harrowing unit's operating speed on uniformity of cultivation depth during tillage in fallow field

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Abstract. Retention of soil moisture is an urgent topic of the day in the cultivation of agricultural crops. Using fallow fields is one of the ways to solve the named problem, but the tilling of such fields requires observing some special conditions, in particular, the capillary effects in their upper soil layers must be cut down. For that purpose, the authors have proposed a special harrow equipped with the tools capable of fulfilling the above-mentioned task. The authors have carried out extensive field experiment research into the tillage of fallow soils with the use of the said implement. In order to apply the implement, a new harrow unit has been developed. The results obtained during the experiment research have been processed with the use of statistical methods and it has been established that the depth of harrowing in the tilled field decreases, when the operating speed of the combined unit under consideration increases to 3.3 m s^{-1}. At the same time, the variances of oscillations of the parameter under research in accordance with the Cochran's C test remain uniform. Also, the frequency of the harrowing depth oscillations changes insignificantly. That is supported by the correlation lengths of the normalized correlation functions of the process under consideration, which, at the above-mentioned operating speed, stay within the sufficiently narrow range of values: 0.16–0.20 m. According to the results of the experimental investigations, the maximum value of the normalized cross-correlation function for the relation between the oscillations of the field harrowing depth and the oscillations of the field's longitudinal profile does not exceed 0.12. This testifies to the absence of any substantial interrelation between the said two stochastic processes, which is quite reasonable in view of the small values of the variance and period of the oscillations of the field's longitudinal profile. The probability of the new combined tractor and harrow unit maintaining the tolerance of the fallow field cultivation depth oscillations within the range of ± 1 cm is equal to 82%. Within each 1.85 m of the distance travelled by the combined soil cultivation unit under consideration, only one instance of the field cultivation depth deviating from the ± 1 cm tolerance can be expected.

Key words: fallow, field profile, harrow, operating speed, tillage depth.

INTRODUCTION

As a result of the numerous field investigations, it has been established that, even at a sufficient amount of plant nutrients, the scarcity of soil moisture results in the reduced yield of the agricultural crops (Donaldson et al., 2001). In the absence of water in the soil, the sowing is either put off to some later date or completely postponed until spring (Schillinger & Papendick, 1997).

One of the ways to retain and even, to some extent, accumulate moisture in the soil is to apply the fallow land practice (Chang et al., 1990). The ripping of the upper soil layer up to the mulch condition virtually destroys its capillarity, which results in the development of the medium that separates the damp and relatively cold layer of soil from the dry and warm ground air. Under such conditions, the dissipation of water content from the uncultivated layer of soil gets substantially lower (Massee et al, 1978; Al-Mulla et al., 2009).

There are different kinds of agricultural machines for producing such soil mulch. Most commonly, they are equipped with V-blade tools, each one with a working span of 46 cm and more (Smith et al., 1996; Schillinger et al., 2006). Sometimes, rod weeders are applied as well as disc harrows and chisel cultivators (Lindwall & Anderson, 1981; Carman, 1997; Kornienko et al., 2016; Lovarelli & Bacenetti, 2017; Tagar et al., 2020).

The primary drawback of these implements is that they operate steadily only at a soil cultivation depth of greater than 10 cm. But it was as long ago as in 1909 that Russian scientist I. Ovsinskiy (1909) convincingly proved that the depth of the soil mulch might not exceed two inches, i.e. it had to be between 5 to 6 cm. From the previous field experiments, it has been established that this soil mulch layer is exactly the place, where the intensive water evaporation from the tilled soil takes place (Nadykto et al., 2012).

Moreover, it has to be taken into account that, when the field is tilled to a depth of 6 to 7 cm, the stirring of the soil and especially the carryover of its water content to the daylight surface of the field have to be kept to a minimum. Meanwhile, the numerous field experiments have shown that, even when single-row disc tools (Smith et al., 1996; Moreno et al., 2011) or bar harrows (Schillinger & Papendick, 1997) are used which in principle capable of tilling soil to the required depth of 6 to 7 cm, the discussed problem is still not solved completely. It results mostly from the fact that they rather intensively stir the cultivated soil layer (which is especially true for disc harrows).

MATERIALS AND METHODS

Taking into account the above-mentioned circumstances, the authors have developed an implement for cultivating fallow land, comprising different harrowing sections (Fig. 1), with each section containing 20 tools (5 rows with 4 tools in each of them) attached to the frame following a zigzag harrow pattern.

The tool in the section is a flat bar (spike tooth) with a thickness of 8 mm, to which a flat blade with a working width of 80 mm is welded. The front row of tools in the section can be equipped with vertically set blades. Such alignment of the front blades of the section facilitates cutting (shredding) those plant residues, which can be present in the upper (to a depth of up to 6 to 7 cm) soil layer. That action provides for the more stable motion of the harrowing section in the longitudinal and vertical plane.

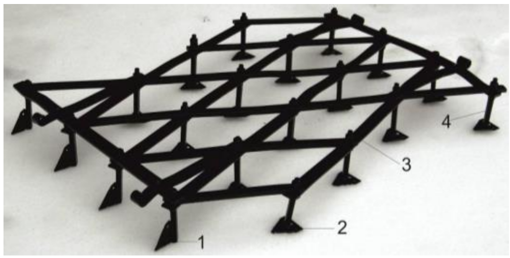

Figure 1. Isometric view of the proposed harrowing implement: 1 – vertically set blade; 2 – horizontally set blade; 3 – harrow frame; 4 – tool.

Each section is attached with the use of two drag bars to the common beam, the latter, in its turn, is connected with the carrying tractor. One of the problem points in the operation of such a harrowing section is the stability of its position in the longitudinal and vertical plane, when performing the harrowing operation.

In view of that, the aim of this study was to investigate theoretically and experimentally the effect of the operating speed of the developed harrowing unit on the uniformity of the soil ripping depth during fallow field tillage.

Figure 2. Combined tractor and harrow unit during fallow field tillage.

The experimental investigations were carried out during the spring harrowing of fallow fields. The fallow land was preceded by sunflower fields, the last soil tillage operation was mouldboard ploughing to a depth of 25 cm. In order to carry out the field investigations, a cultivated field with an area of 70 ha was selected, in which, prior to the experiments, multiple measurements of the moisture content and density of the soil in its upper 0–10 cm layer were made and also the longitudinal profile of the cultivated land was measured.

In the field experiment investigations, the harrowing unit for fallow land tillage was used, which comprised a wheeled tractor (MTZ-82, 60 kW) and the developed harrow, which included 9 harrowing sections (Fig. 2). In the process of the field investigations, the harrowing unit travelled using three different gears, which enabled its movement at three different speeds.

Specification of the harrowing unit:

Number of harrowing sections	9
Working width of section	0.91 m
Formation of sections in unit	line
Spacing between sections	0.06 m
Working width of harrowing unit	8.70 m

The following values were measured with three replications at each operating speed of the harrowing unit: the time t_a, in which the harrowing unit passed the recorded distance with a length of 250 m and the soil cultivation depth.

The time t_a was measured with the help of an FS-8200 electronic stopwatch with a measurement accuracy of ± 0.1 s. Then the operating speed of the combined tractor-implement unit V_a was calculated by the formula:

$$V_a = \frac{s}{t_a}. \quad (1)$$

The soil moisture content in the layer of 0–10 cm was measured with the use of the SHS-1 instrument, which was connected to the personal computer via the Arduino Uno interface unit (Fig. 3). The error in the measurement of the absolute value of the soil moisture content with the use of the SHS-1 instrument did not exceed ± 1%.

The data received from the Arduino Uno were transformed with the use of the CoolTerm software into the format suitable for the processing in the Microsoft Excel environment. After 100 soil moisture content measurements, taken at each 3 m, when moving along the diagonal of the field, had been completed, the mean value of the moisture content was calculated.

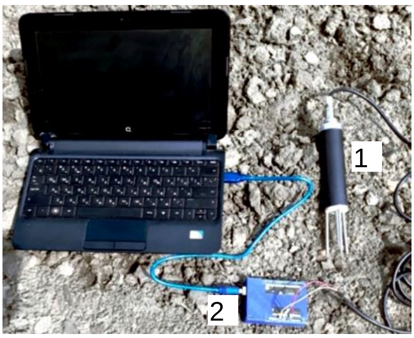

Figure 3. Soil moisture content measuring kit: 1 – SHS-1; 2 – Arduino Uno.

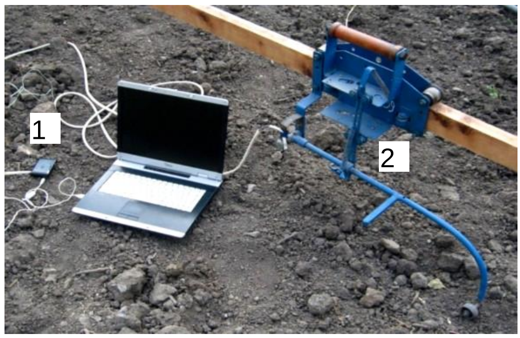

Figure 4. Device for measuring field profile oscillations: 1 − Arduino Uno; 2 – profilometer.

The longitudinal profile of the tilled field was measured with the help of a developed profilometer (Fig. 4). It was mounted on a rail positioned in parallel to the field surface. The lever of the instrument touched with its one end the surface of the field (i.e. sensed the profile), while the other end was pivoted to the axle connected to an SP-3A variable resistor. The resistor had a straight-line characteristic and a nominal value of 470 Ω.

As the instrument moved along the rail, the lever performed oscillatory motion in the longitudinal and vertical plane, which resulted in the variation of the resistance value in the SP-3A. The electric signal that was output in this process was sent to the analogue input of the Arduino Uno, then transmitted to the PC, where it was transformed to make it suitable for the processing in the Microsoft Excel environment.

The oscillations of the longitudinal profile of the field were recorded with 5 replications at a measurement interval of 0.1 m. With a rail length of 4 m, it provided for obtaining at least 350 points. The error in the measurement of the field profile oscillations with the use of the described instrument did not exceed ± 0.5 cm.

The density of the soil in the 0–10 cm layer was measured in accordance with the technique that is detailed in the paper.

For each operating speed of the combined tractor and harrow unit under consideration, three series of soil cultivation depth measurements were carried out. Each series comprised 200 measurements at an interval of 0.2 m. The accuracy of the instrument applied for this purpose (Fig. 5) was equal to ± 0.5 cm. The process of operating the instrument is as follows. For the purpose of taking a measurement, the cross bar 1 (Fig. 5) of the instrument is placed on the soil surface. Using the lever 3, the rod 4 is manually lowered until it is stopped by the untilled soil. After that, the value of the soil tillage depth is read on the measuring scale 2.

Figure 5. Instrument for measuring tillage depth: 1 – cross bar; 2 – measuring scale; 3 – lever; 4 – rod.

Apart from the standard statistical characteristics, normalized correlation functions were calculated for the tillage depth. These functions provide for estimating the frequency spectrum of the harrowing depth oscillation process. The impact of the field profile oscillations on the depth of its cultivation was estimated with the use of the normalized cross-correlation function.

RESULTS

The experimental investigations were carried out on dark chestnut soil in the conditions that were close to arid. The soil texture was heavy clay loam, since the alphitite content in the soil was at a level of 46–48%. The humus content was at a level of 2.8–3.6%, the reaction of soil solution was close to neutral.

At the time, when the experimental investigations were carried out, the mean value of the soil water content in the 0–10 cm layer was 18.3%, while the mean value of the soil bulk density in the same layer was 1.24 g cm^{-3}. The variance of the field surface profile oscillations was equal to 0.54 cm^2. The mean value of the period of the oscillations was equal to 0.17 m. When the combined harrow unit under consideration operated on such moving at different speeds of translation, the harrowing depth had the parameters presented in Table 1.

The analysis of the data from the table provides evidence of the following facts. When the operating speed was changes from 2.1 to 2.5 m s^{-1}, the mean value of the harrowing depth decreased by 0.2 cm. At a statistical significance level of 0.05 (that is, at a confidence coefficient of 95%), such a difference is non-random and significant, because in this case LSD_{05} is lower and equal to 0.1 cm.

As regards the mean value of the harrowing depth in the case, when the combined tractor and harrow unit travels at an operating speed of 3.3 m s^{-1} (Table 1), the null hypothesis of its equality to the two other statistical characteristics (5.0 and 4.8 cm) is rejected even at a statistical significance level of 0.01. That can be explained by the wider confidence interval for the mean value of the soil cultivation depth at the unit's travel rate of 3.3 m s^{-1} (Table 1).

Table 1. Statistical characteristics of harrowing depth

Operating speed, m s^{-1} (km h^{-1})	Confidence interval, cm	Variance, cm^2	Standard deviation, ± cm	Coefficient of variation, %	Error of mean, cm
2.1 (7.6)	5.0 ± 0.1	0.49	0.70	14.0	0.06
2.5 (9.0)	4.8 ± 0.2	0.52	0.72	15.0	0.07
3.3 (11.9)	4.0 ± 0.3	0.58	0.76	19.0	0.06

The above-said leads to a conclusion that increasing the rate of travel of the combined tractor and harrow unit under investigation results in the decrease of the harrowing depth in the field under cultivation (Fig. 6). At the same time, the confidence interval for the said parameter demonstrates the uptrend.

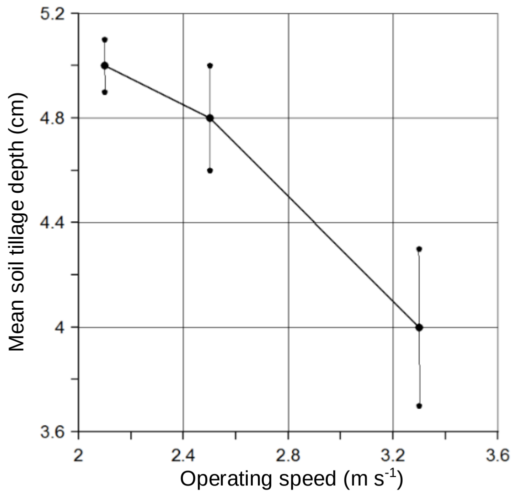

Figure 6. Relation between mean soil tillage depth and combined tractor and harrow unit's operating speed.

In the discussed case, the described result can a priori be explained only by the suggestion that the towed members of the process part of the combined tractor and harrow unit under consideration (that is, the harrowing sections) tend to shallow up from the soil, when its rate of travel increases. It must be emphasized that such a phenomenon is quite common in the operation of towed implements.

The variance and correlation analysis of the results obtained during the field experiment investigations carried out by the authors provides evidence of the following facts:

1. At a confidence level of 95% and greater, it can be stated that the null hypothesis of the equality of the compared variances of harrowing depth oscillations in the cases, when the soil cultivation unit travels at rates of 2.1 and 2.5 m s^{-1}, is not rejected. And that is true, because the actual value of the Fisher's ratio test F_r = 0.52 cm^2/0.49 cm^2 = 1.06 is smaller than the table value F_{tabl} = 1.39.

2. The three compared variances of harrowing depth oscillations do not significantly differ from each other. The statistical analysis shows that according to the Cochran's C test even the greatest of the discussed statistical characteristics (0.58 cm^2, Table 1) is uniform with the other two. As shown by the calculations, the actual value of the above-mentioned criterion for this case G_r = 0.58/(0.49 + 0.52 + 0.58) = 0.36 is smaller than the table value, which is equal to 0.58 at a statistical significance level of 0.05.

3. The harrowing depth oscillations during the operation of the unit under research take place within approximately the same frequency range. The basis for such a univalent conclusion is provided by the behaviour of the respective normalized correlation functions (Fig. 7).

The principal characteristic property of each of the functions is the correlation length, that is, the distance from zero to the first point of intersection between the function and the axis of abscissa.

It becomes evident from the analysis of the obtained correlation functions that the correlation length for all the three modes of motion of the discussed combined tractor and harrow unit is roughly the same. Despite the difference between the operating speeds of the harrowing unit (2.1, 2.5, and 3.3 m s^{-1}), these characteristics in terms of their values (correlation lengths) are situated in a sufficiently narrow range: 0.16–0.20 m (curves 1, 2, and 3, Fig. 7).

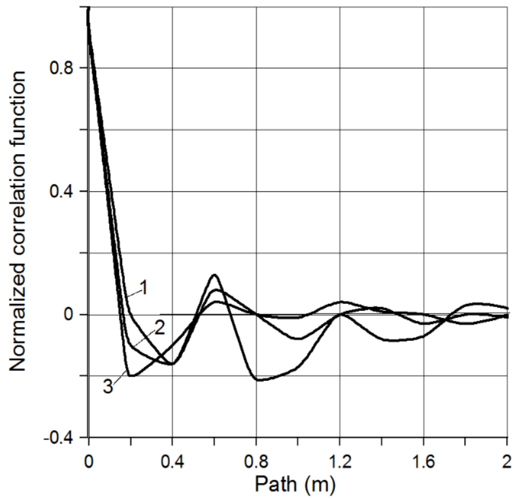

Figure 7. Normalized correlation functions of tillage depth oscillations at different operating speeds of combined tractor and harrow unit: 1) 2.1 m s^{-1}; 2) 2.5 m s^{-1}; 3) 3.3 m s^{-1}.

Nevertheless, taking a formal approach to the analysis of the obtained correlation functions it has to be noted that, as the rate of move of the soil cultivation unit under research increases, the spectrum of the harrowing depth oscillations spreads out to some extent. For example, while at the unit's operating speed of 2.1 m s^{-1} the correlation length of the process under consideration is equal to approximately 0.20 m (curve 1, Fig. 7), the increase of the unit's travel rate to 3.3 m s^{-1} results in this length decreasing to about 0.16 m (curve 3, Fig. 7). Essentially, that means that the spectrum of the harrowing depth oscillations in the latter case is to some extent wider. But the noted difference is small, therefore, it can be stated that the change of the harrowing unit's operating speed from 2.1 to 3.3 m s^{-1} has virtually no effect on the frequency of the soil cultivation depth oscillations during the operation of the unit under research.

One more statistical measure used for stationary ergodic processes is the cross-correlation function. As is known, in case of two stochastic processes $X_1(t)$ and $Y_1(t)$, this function describes the degree of correlation between the section of the process $X_1(t)$ at $t = t_1$ and the section of the process $Y_1(t)$ at $t = t_2$.

In the described research, the authors investigated the statistical interrelation between such stochastic processes as the oscillations of the tilled field profile in the longitudinal and vertical plane and the oscillations of the harrowing depth. Hypothetically, it could be expected that the two processes had a close correlation.

In effect, it was established that, in the case under consideration, virtually no closeness is observed in the above-mentioned correlation (Fig. 8).

For example, the level of the coefficients of the correlation between the field profile oscillations and the oscillations of the harrowing depth only slightly exceeds the 0.1 point. And that observation is true both for the positive (first and second quadrants, Fig. 8) and negative (third and fourth quadrants, Fig. 8) levels of the analysed correlation. Again, the presence of roughly identical, in terms of their values, maximum and minimum of the cross-correlation function excludes the possibility to determine, which of the processes is the input process and which is the output one.

This point needs to be analysed in greater detail. As is seen in Fig. 8, the cross-correlation function reaches its maximum negative value at a level of – 0.12, when its phase displacement is equal to approximately – 0.2 m (pt. A, Fig. 8). If the maximum of the positive correlation was at the same time below 0.12, it would be possible to state that the harrowing depth is the input factor, while the field surface profile is the output one. Moreover, in case of the negative correlation the situation is as follows: the greater the oscillations of the field surface irregularities, the smaller harrowing depth oscillations. Obviously, it would be very difficult to give a logical explanation for such a result.

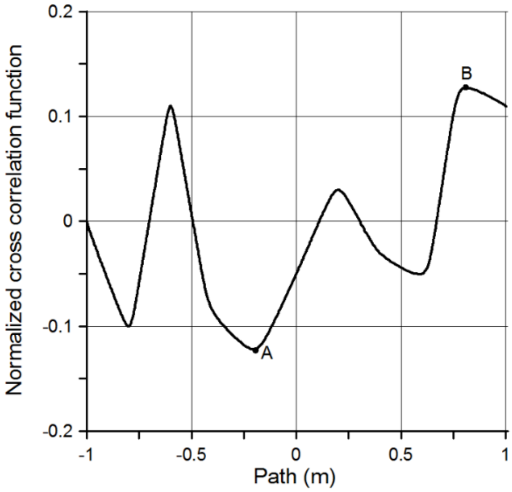

Figure 8. Normalized cross-correlation function for oscillations of longitudinal field profile and tilling depth.

On the other hand, the cross-correlation function reaches its maximum positive value at a level of 0.12 at a phase displacement of about 0.85 m (pt. B, Fig. 8). If the maximum of the negative correlation (its absolute value) was at the same time smaller and not equal to that of the positive correlation, the following conclusion could be arrived at: in case of a positive correlation, the profile irregularity oscillations are the input action, while the harrowing depth is the output action. The phase displacement in this case is equal to 0.85 m. In practical terms, that means that at a operating speed of, for example, 2.5 m s^{-1}, the time lag in the reaction of each harrowing section of the soil cultivation unit to the oscillations of the field profile irregularities in the longitudinal and vertical plane is equal to 0.85 m /2.5 m s^{-1} = 0.34 s.

When the maximum values of the negative and positive correlations in the cross-correlation function under consideration are equal, those statements are not true. Moreover, taking into account the very low maximum level of the normalized cross-correlation function, which does not exceed the 0.12 mark (Fig. 8), it is possible to state that, in the process of the research completed by the authors, no significant correlation was found between the oscillations of the profile irregularities of the cultivation field in the longitudinal and vertical plane and the oscillations of the depth of its harrowing.

The above result can be explained as follows. As earlier noted, the mean value of the period of the field profile irregularity oscillations during the research was equal to 0.17 m, while their variance was equal to 0.54 cm^2. The length of one harrowing section, which was equal to 1.2 m, contained 7 such periods. In view of that and taking into account the rather small variance of the track profile oscillations, it was quite logical to expect that the statistical characteristics of those oscillations could not have a significant effect on the oscillations of the soil cultivation depth.

When the soil is cultivated to a depth of 5–6 cm, the working tolerance for the oscillations of this parameter has to be low. The authors have set it at a level of $\Delta = \pm 1$ cm. In that case, it would be useful to know the probability P (%) of the harrowing unit maintaining such a tolerance and the frequency of deviating from it (ω, m^{-1}).

The first of the above-mentioned indicators can be calculated by the following formula (Lurye, 1970):

$$P = 2 \cdot F\left(\frac{\Delta}{\sigma}\right), \qquad (2)$$

where F − Laplace's integral function; Δ – working tolerance for the oscillations of soil tillage depth (± cm); σ – standard deviation of the fallow field tillage depth (± cm).

In order to calculate the second indicator (that is, ω) the following relation is used (Lurye, 1970):

$$\omega = \frac{1}{2 \cdot T_p} \cdot exp\left(-\frac{\Delta^2}{2 \cdot \sigma^2}\right), \qquad (3)$$

where T_p − half period of the soil tillage depth oscillation. If the correlation function of the process is known, the value of T_p can be found as follows:

$$T_p = \frac{1}{n} \cdot \sum_{i=0}^{n} (\tau_{i+1} - \tau_i), \qquad (4)$$

where n – number of points of intersection between the normalized correlation function curve and the axis of abscissae; τ_i – successive values of the coordinates, at which the correlation function curve crosses the X-axis. For the normalized correlation functions shown in Fig. 7 the mean value of this parameter is T_p = 0.36 m.

As the mean value of the parameter σ in the case under consideration is equal to 0.73 (Table 1), the following value of the ratio is arrived at:

$$\frac{\Delta}{\sigma} = \frac{1}{0.73} = 1.37.$$

Then, in accordance with the well-known table, the value of Laplace's function is equal to 0.41. In view of the above-said, the expression (2) gives the following result: P = 0.82. In practical terms, that means that the probability of the combined unit under consideration maintaining the working tolerance of the soil cultivation depth at a level of ± 1 cm is equal to 82%.

Pursuant to the expression (4), at T_p = 0.36 m, Δ = ± 1 cm and σ = ± 0.73 cm the value of ω is equal to 0.54 m^{-1}. The obtained result has to be interpreted as follows: in each 1/0.54 = 1.85 m of the travelling track of the soil cultivation unit under consideration, one instance of the harrowing depth deviating from a tolerance of ± 1 cm is possible.

CONCLUSIONS

When selecting the conditions of the harrow unit, it should be taken into account that increasing the operating speed results in the decrease of the harrowing depth in the cultivated field, while the variances of oscillations of the above-mentioned parameter in accordance with the Cochran's C test remain uniform. The frequency of the harrowing depth oscillations changes little. That is confirmed by the values of the correlation lengths in the normalized correlation functions of the process under consideration, which, in case of the above-mentioned mode of travel of the combined tractor and harrow unit, stay within the sufficiently narrow range: 0.16–0.20 m.

Following the results of the experimental investigations, the maximum value of the normalized cross-correlation function representing the relation between the oscillations of the field harrowing depth and the oscillations of the field's longitudinal profile does not exceed the 0.12 mark. That gives evidence of the absence of a significant interrelation between the two stochastic processes, which is quite reasonable in view of the small values of the variance and period of the longitudinal field profile oscillations.

The probability of the new combined tractor and harrow unit maintaining the tolerance of the fallow field cultivation depth oscillations within the range of ±1 cm is equal to 82%. Within each 1.85 m of the distance travelled by the combined soil cultivation unit under consideration, only one instance of the field tillage depth deviating from the ± 1 cm tolerance can be expected.

The above results of research can be used as practical guidelines, when selecting the unit's mode of travel in terms of its speed for ripping the soil to a depth of up to 6–7 cm. In case these guidelines are followed, the operation of the unit at speeds within the investigated range (2.1–3.3 m s^{-1}) will result in the high quality of soil tillage.

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