

Article

Experimental Investigation of Plow-Chopping Unit

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Abstract: The article presents research results of a machine-tractor unit that performs two technological operations simultaneously: (i) chopping plant residues (sunflower stubble); (ii) covering the chopped stubble with the soil. The first operation is carried out with a front-mounted plant residues chopper, and the second one is carried out with a rear-mounted plough. The chopper's working devices are rotated by the tractor's front power take-off (PTO), which has two operating modes: 540 and 1000 rpm. It was determined that to reduce the dynamic load in the drive of the chopper's plant residues working devices, to chop these residues qualitatively, and then to cover them with the soil, the tractor's front PTO should be adjusted to a speed of 1000 rpm. With this mode of the chopper's working device's rotation, the difference in its vertical vibrations' dispersion and the tractor front axle's oscillations is insignificant. The variance of the plowing depth vibrations (1.44 cm^2), changing aperiodically in the frequency range of 0–2.5 Hz, is not accidentally less than the variance of irregularities vibrations of the longitudinal field profile (2.75 cm^2). The plough draft resistant oscillations of the plow-chopping unit had the least impact at the plowing depth oscillations. The proof of this is the small value of the cross correlation function; for such oscillating processes as 'plough draft resistance—plowing depth', it was equal to 0.22, which is 3.4 times less than for oscillating processes 'surface's longitudinal profile—plowing depth'. The number of chopped particles less than 15 cm in length increased by 1.5 times, and the number of particles longer than 30 cm decreased by 3 times. With the complete incorporation of plant residues into the soil, their non-chopped part did not exceed 1%.

Keywords: front chopper; surface's longitudinal profile; plough draft resistance; plowing depth



Citation: Bulgakov, V.; Aboltins, A.; Beloev, H.; Nadykto, V.; Kyurchev, V.; Adamchuk, V.; Kaminskiy, V. Experimental Investigation of Plow-Chopping Unit. *Agriculture* **2021**, *11*, 30. <https://doi.org/10.3390/agriculture11010030>

Received: 4 December 2020

Accepted: 26 December 2020

Published: 4 January 2021

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1. Introduction

Production tractors with front and rear hitch linkages allow creating perspective tractor-machine units according to the scheme 'push-pull'. While using such units, instead of ballasting the front axle of the tractor, the vertical component of the traction resistance of the front-mounted agricultural machine is used. However, this occurs only when the tractor and such machines are put together correctly.

The emerging agricultural machines operating in a pushing mode make it necessary to develop the appropriate theoretical bases for their practical use [1–4]. In this case, the main problem is to exclude vertical unloading of the tractor's front wheels [5–7] and to

ensure satisfactory front machine penetration into the soil [1]. Otherwise, the 'push-pull' unit can be poorly controlled and is unstable in work.

The first and most prevalent units put together according to the scheme 'push-pull' are plowable. For their comprehensive implementation, many world-known companies produce special front ploughs (www.jwi.co.uk/machinery). However, their use simultaneously with rear-mounted ploughs allows performing only one technological operation, i.e., plowing.

Simultaneously, one of the 'push-pull' scheme's perspectives is the design of units that simultaneously perform two different technological operations. One of which is the chopping of plant residues and their incorporation into the soil.

Until recently, these operations were performed by different units separately. In their research, scientists, first of all, established the energy consumption required for chopping various plant residues [8–11]. For example, testing a rotary cutter has shown that with an energy consumption of 5 kW m^{-1} , the range of this indicator oscillations can reach $\pm 30\%$ [9].

The perspective of using a roll-chopper for chopping cover crops was considered in the article [12]. It has been found that this machine can be used in combination with other weed management strategies such as selective herbicide application.

The test results of the pull-type residues chopper MZ6000 (Bednar, Czech Republic), which has three vertical rotors and a working width of 6 m, are presented in article [13]. Researchers emphasize that this plant residue chopper's energy consumption level can obtain 13.3 kW m^{-1} and even more.

Besides pull-type and rear-mounted plant residue choppers, examples of front-mounted cutters use are known. In article [14], the tractor's driving stability with such a machine is investigated.

Using a front-mounted chopper with a vertical rotor as part of a sugar beet harvesting unit is discussed in article [15].

There is a rotary machine, which chops corn stalks and covers them with soil. However, the amount of coverage of these residues does not exceed 30% [16].

The covering of plant residues with the soil is carried out in several ways. Quite often, this process is carried out with disc harrows. Usually, farmers are recommended the variant of these machines with two rows of discs [17].

Sometimes, machines with active working devices in the form of cutters are used [18]. Moreover, they are even used in the controlled traffic farming system [19].

Strictly speaking, when using disc and milling working devices, it is not so much the incorporation of plant residues into the soil that occurs when they are mixed with the crushed soil. Simultaneously, it is more efficient to completely place these residues in an anaerobic environment (i.e., deep). Conventional plows are known as the best for this task [20]. A unique effect occurs when using two-deck ploughs [21].

Considering the above, we attempt to design a machine-tractor unit that chops plant residues (stubble of agricultural crops) and covers them simultaneously with the soil with a plough. This unit's difference is that the first operation is carried out by a front-mounted chopper of plant residues mounted on the tractor. The second technological operation is carried out with a rear-mounted plough. Theoretical premises such as the tractor-machine unit are detailed in the article [22].

Further effective use of the plow-chopping unit developed by us requires solving some scientific problems. The first one is to determine the rotation mode of the chopper working devices. Because they are driven with the tractor's front power take-off (PTO), it is needed to determine its rotation mode: 540 or 1000 rpm.

The second research task is to study the plant residue frontal chopper's effect on the tractor's front axle vertical oscillations. The solution to this issue will determine the chopper's moving equability in a vertical plane and its possible influence on oscillations in the plowing depth.

The next task is to determine the plowing depth stability dependence on the field's longitudinal profile vertical oscillations and the plow's draft resistance's longitudinal oscillations.

Finally, a significant issue is the study of plant residues' chopping quality before covering them with the soil. Thus, this article is devoted to the solution to these four problems. It should be noted that until now no one has carried out a comprehensive solution to these problems concerning the tractor-machine unit.

2. Material and Method

2.1. Brief Plow-Chopping Unit Performance

The plow-chopping unit consists of HTZ-16131 (Kharkiv, Ukraine) tractor, which is equipped with front and rear three-point hitch linkages and the front power take-off (PTO, Table 1). Designed by us, the frontal plant residues chopper was mounted on the front tractor's three-point hitch linkage, and the PLN-5-35 (Alex-Agro, Ukraine) five-bottom plough was mounted on the rear one (Figure 1).



Figure 1. Plow-chopping unit.

Working devices of the PRR-1.5 chopper (Melitopol, TSATU, Ukraine) are rotated by cardan shaft from the HTZ-16131 tractor's PTO. It has two operating modes: 540 and 1000 rpm.

Before the research, the working devices of the PRR-1.5 chopper were started in three replicates on each of these modes. Simultaneously, the PRR-1.5 was in the raised (transport) position and did not chop plant residues.

Table 1. Technical characteristic of the plow-chopping unit.

Tractor HTZ-16131:	
Power Engine (kW)	132.4
operating mass (kg)	7800
front wheels track (mm)	2100
rear wheels track (mm)	2100
front wheels: tire size	16.9R38
air pressure (bar)	1.3
rear wheels: tire size	16.9R38
air pressure (bar)	1.1
PTO operating mode (rpm)	540
	1000
Chopper PRR-1.5:	
operating mass (kg)	400
working width (m)	1.70
Plough PLN-5-35:	-
operating mass (kg)	800
plough bottoms number	5
working width (m)	1.75

2.2. Starting Torque Determination of the Chopper Working Devices

These were the next measured parameters: (i) torque on the PRR-1.5 working devices drive shaft; (ii) time (t_s) from the point of the beginning to the point of steady movement of the chopper's working devices.

To measure the torque, we used the shaft with a strain gauge transducer glued to it according to the full-bridge scheme.

The electrical signal from the strain-measuring bridge was entered into an Arduino Uno device (Torino, Italy) and then into a laptop. After that, obtained data were formatted with the program CoolTerm (Roger Meier, version 1.7.0. <https://freeware.the-meiers.org/>) for processing in the Microsoft Excel (Microsoft Office Excel 2010, Windows, USA) environment.

To measure time t_s , an FS-8200 (China) electronic stopwatch with an accuracy of ± 0.1 s was used.

2.3. Main Mode Operation of the Plow-Chopping Unit

Experimental studies were carried out after sunflower harvesting. These parameters were measured: (i) moisture and bulk density of the soil in layer 0–1030 cm; (ii) height of sunflower stubbles; (iii) oscillations of the surface's longitudinal profile.

The absolute value of soil moisture was measured with the SHS-1 sensor (Kharkiv, Ukraine), which was connected to a laptop via an Arduino Uno (Torino, Italy) device (Figure 2). The error of measuring this parameter does not exceed $\pm 1\%$.

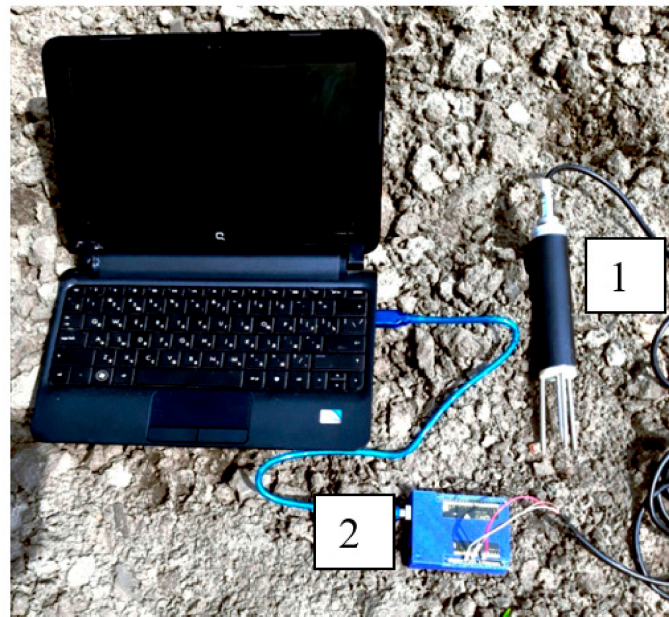


Figure 2. Soil moisture measuring kit: 1—SHS-1; 2—Arduino Uno.

The surface's longitudinal profile's vertical oscillations were measured with a unique device (Figure 3) constructed by us. It was mounted on a wooden bar parallel to the field surface. One tip lever of this device contacted the field surface, and the other one was fixed with a horizontal pivot on an axis connected with potentiometer SP-3A (Kharkiv, Ukraine). Its resistance is equal to 470Ω .

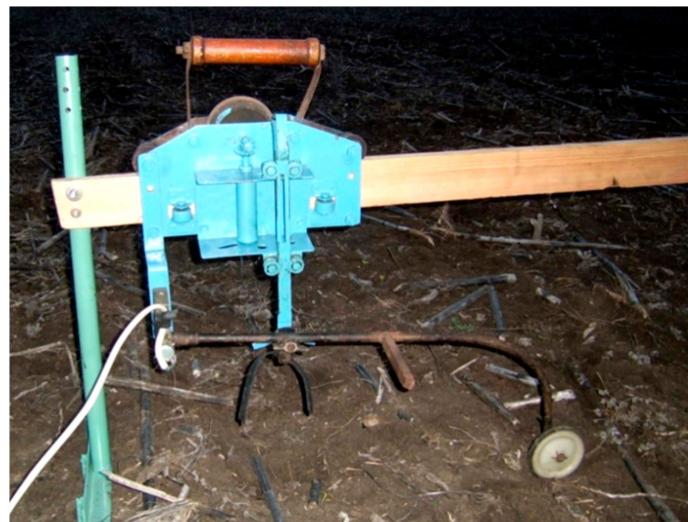


Figure 3. Device for measuring surface profile oscillations.

While the device is moved along the wooden bar, the lever oscillates in the longitudinal vertical plane, thereby changing the SP-3A resistance value. The electrical signal enters the Arduino Uno's analog input and then is transferred to the laptop with a subsequent conversion for processing in the Microsoft Excel environment.

During the calibration of this device, the distance between the lever's wheel and the supporting surface was changed in the range of 0–10 cm with an interval of 1 cm. For this, nine wooden blocks were used, in which the height of the next one differed by 1 cm from the height of the previous one. During the installation of each bar, an electrical signal was recorded, formed by the SP-3A potentiometer. As a result, a dependence was obtained that

made it possible to determine the field profile's height by the magnitude of the electric signal.

The oscillations of the surface's longitudinal profile were recorded in three replicates with a measurement step of 0.1 m. This made it possible to obtain at least 350 points with a wooden bar length of 4 m. The measurement error of the surface profile oscillations with this device does not exceed ± 0.5 cm.

According to the article's method [18], soil moisture was measured in the 0–1030 cm layer. The stubble sunflower height was measured diagonally along the field using a ruler. This parameter's measurement accuracy was equal to ± 0.5 cm; the measurement step was 1 m; the number of measurements was 250.

Sites were prepared on the field, each 300 m long. On the first 25 m of the site, the unit was accelerated to a steady motion. On the site with a length of 250 m, the plow-chopping unit performed a working stroke. The rest of the way (about 25 m) was intended to stop the unit. It was decided to use the forward speed of the plow-chopping unit, as this is possible under reasonable working conditions.

During the moving of the plow-chopping unit, there were measured in three replications: (i) time (t_a) of the plow-chopping unit passing the test site of length $S = 250$ m; (ii) vertical oscillations of the tractor's front axle; (iii) plough's draft resistance.

An FS-8200 electronic stopwatch was used for measuring time t_a . The tractor-machine unit's working speed was calculated with the Equation (1):

$$V_a = S/t_a \quad (1)$$

The tractor's front axle's vertical vibrations recording was carried out using an ADXL345 accelerometer (Adafruit, New York, USA) (Figure 4).

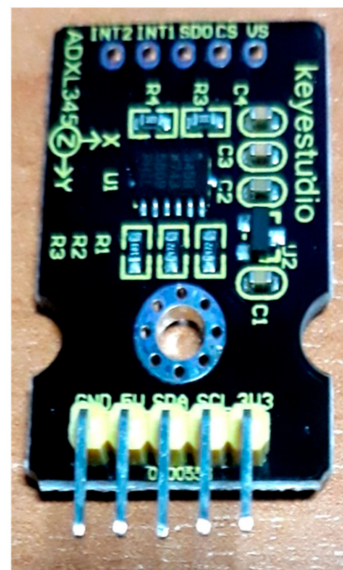


Figure 4. ADXL345 accelerometer.

It has a high resolution (4 mg LSB^{-1}) and a working range from $\pm 2 \text{ g}$ to $\pm 16 \text{ g}$. In this case, the electrical signal enters the Arduino Uno's analog input and then is transferred to the laptop with a subsequent conversion for processing in the Microsoft Excel environment.

During the calibration process, the accelerometer was fixed on a platform, which vibrated in the vertical plane under the cam-eccentric drive's influence. The vibration amplitude of the platform was changed by increasing the length of the eccentric. The platform oscillation frequency was taken equal to 1.6 Hz (10 s^{-1}).

To measure the plough's draft resistance, we used a strain-measuring sensor designed for a draft of 40 kN (Figure 5). The electrical signal from this sensor entered the laptop through the Arduino Uno device. The signal sampling rate was 0.1 s .

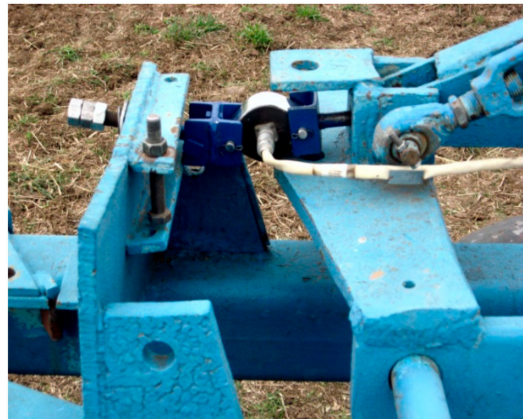


Figure 5. Strain-measuring plough.

After the passage of the plow-chopping unit, three series of the tillage depth measurements were carried out. The number of each sample was 200 measurements with a step of 0.2 m. The error of the device used in this case (Figure 6) was ± 0.5 cm.



Figure 6. Instrument for measuring tillage depth.

During investigations, the sunflower stubble chopping degree by the PRR-1.5 chopper was estimated. While the unit was moving, the plough was lifted to the transport position. After this, the particles up to 15, 15–30, and more than 30 cm in length were counted. We used a frame with an area of 0.5 m^2 and a ruler with a measuring accuracy of ± 0.5 cm.

For the oscillation values of the surface's longitudinal profile, plowing depth, plough draft resistance, and vertical oscillations of the tractor's front axle, in addition to well-known statistical characteristics, normalized correlation functions and spectral densities were calculated. These make it possible to estimate the frequency composition of the studying process oscillations.

The influence of the surface profile and plough's draft resistance oscillations on the plowing depth was estimated with a cross correlation function. It characterizes the connection level between the cross-section of the process $X1(t)$ when $t = t_1$ and the cross-section of the process $Y1(t)$ when $t = t_2$.

3. Results and Discussion

3.1. Determination of the Operating Mode of the Chopper Plant Residues

Let us consider the torque (M_{pto}) changes, which act on the drive shaft of the PRR-1.5 working devices from the moment they are started. When the front tractor's PTO is set to operate mode 540 rpm, then the torque M_{pto} reaches the maxima value of 200 N m through time $t_s = 0.4$ s (see Figure 7, curve 1).

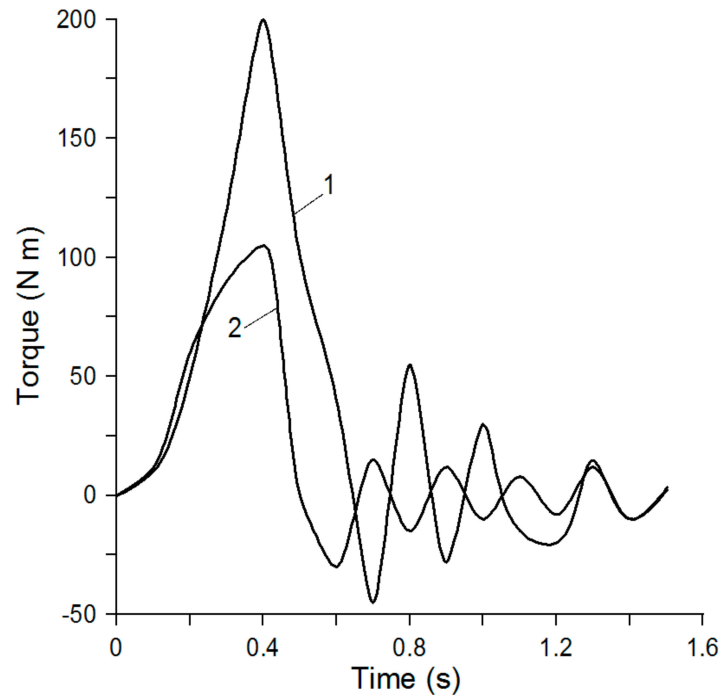


Figure 7. Dynamics torque M_{pto} at the various operating modes of the tractor's front PTO: 1–540 rpm; 2–1000 rpm.

If the front tractor's PTO is set to operate mode 1000 rpm, then the torque M_{pto} reaches the maxima value through time $t_s = 0.4$ s too. (Figure 7, curve 1). However, in this case, its value is almost two times less and is equal to 105 Nm (Figure 7, curve 2).

For subsequent analysis, consider how the torque M_{pto} changes in time. For this purpose, the coordinates' values of the vertical axle (Torque, Figure 7) are replaced with ones that have values (Equation (2)):

$$M_{pto}/t_s, \text{ m}\cdot\text{s}^{-1} \quad (2)$$

The horizontal axle (i.e., time) is herewith unchanged.

The analysis of the obtained data shows when the PTO shank rotates with a frequency of 1000 rpm, the rate of change of the torque M_{pto} reaches its maximum value in 0.2 s (Figure 8, curve 2).

When the tractor's PTO is adjusted to 540 rpm, the maximum rate value of the torque change is reached in 0.4 s. Approximately, 1.3 s after starting the chopper working devices, the change rate of this moment for both PTO settings becomes roughly the same. In general, the rotation mode of chopper's working devices with a frequency of 1000 rpm is preferable. The reason is that at the moment of their start-up, the increasing torque intensity is higher, and the maximum value is much less. The latter circumstance is significant for ensuring the drive reliability of the chopper working devices.

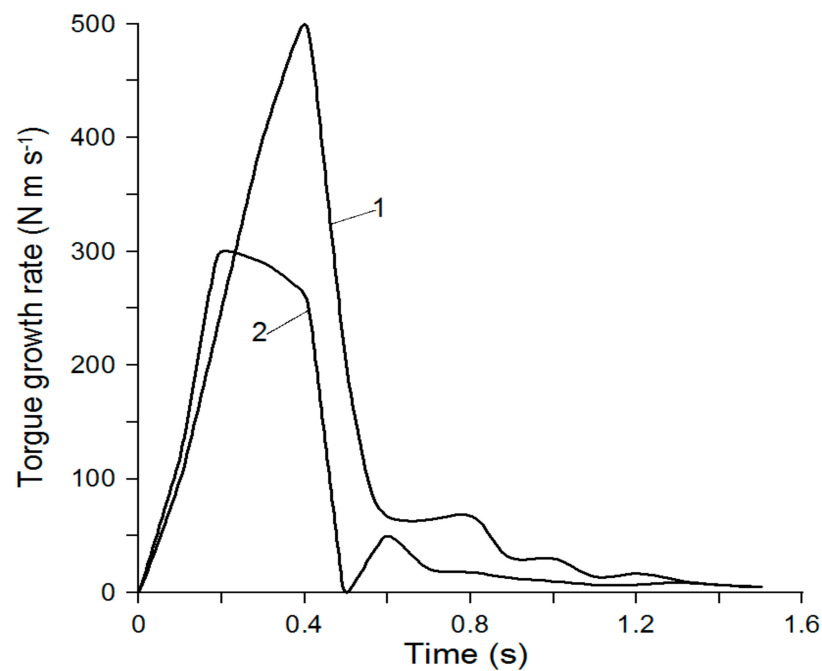


Figure 8. Speed change of torque M_{pto} at the various operating modes of the tractor's front PTO: 1–540 rpm; 2–1000 rpm.

3.2. Field Studies of the Plow-Chopping Unit

Field studies of the plowing-chopping unit were carried out under the conditions presented in Table 2. Experimental studies have established that the surface's longitudinal profile's internal structure oscillations and the plowing depth are practically the same in frequency. Namely, both processes' correlation link length is equal to 0.6–0.8 m (Figure 9).

Table 2. The main characteristics of surface working conditions.

Index	Value
Soil humidity (%)	19.9
Soil bulk density (g cm^{-3})	1.39
Height of sunflower stubble (cm)	43 ± 2
Working speed of plow-chopping unit (m s^{-1})	2.0
Working width of plow-chopping unit (m)	1.76
Plowing depth: mean (cm)	25.0
confidence interval (95%, cm)	25.0 ± 0.3
variance (cm^2)	1.44
standard deviation ($\pm\text{cm}$)	1.20
coefficient of variation (%)	4.8
Plough draft resistance: mean (kN)	25.2
confidence interval (95%, kN)	25.2 ± 0.6
variance (kN^2)	3.61
standard deviation ($\pm\text{kN}$)	1.90
coefficient of variation (%)	7.5

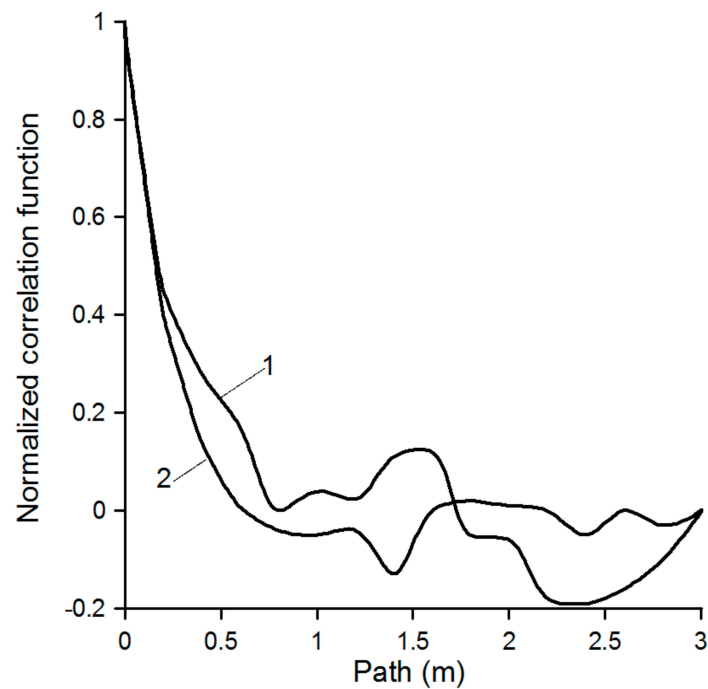


Figure 9. Normalized correlation functions of the surface's longitudinal profile (1) and plowing depth (2) oscillations.

Oscillations of the surface's longitudinal profile and the plowing depth are aperiodic because these processes' normalized correlation functions do not contain periodic components.

The central portion of the variances oscillations of the surface's longitudinal profile and the plowing depth is concentrated in the frequency range of $0\text{--}8\text{ m}^{-1}$ (Figure 10).

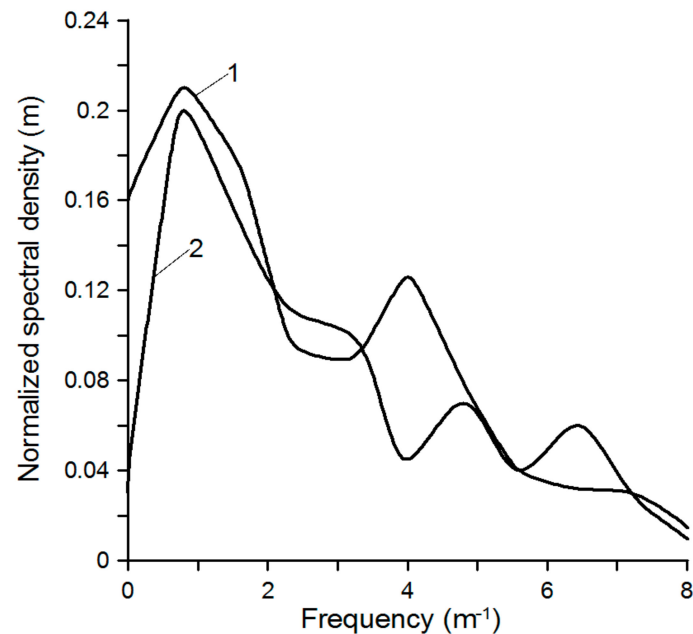


Figure 10. Normalized spectral densities of oscillations of the surface's longitudinal profile (1) and plowing depth (2).

In practice, it is equal to $0\text{--}16\text{ s}^{-1}$ or $0\text{--}2.5\text{ Hz}$ when the operating speed of the plow-chopping unit is $2.0\text{ m}\cdot\text{s}^{-1}$. Such frequency levels are typical for low-frequency processes, that, in our case, are highly desirable.

On the other hand, the oscillations' variances of these compared processes are different. Namely, for the surface's longitudinal profile oscillations, it is equal to 2.75 cm^2 ; for fluctuations of the plowing depth, its value is 1.44 cm^2 . The difference between these variance values is substantial and nonrandom because, according to the Fisher F-test, the null hypothesis about their equality does not reject a significance level 0.05.

The reason for the significant difference between these variances may be the following. During the working pass, the wheels of each 4WD tractor slip in any case. As a result, its front wheels smooth the surface's longitudinal profile. This result allows the tractor's rear wheels to move along a smoother surface and make fewer vertical oscillations. As a result, the vertical oscillations of plowing depth become less too.

To determine the chopper's effect on the tractor's front axle's oscillations, we additionally investigated the plow-chopping unit movement without this implement. It was found that in the presence of the plant residues frontal chopper, the variance of the tractor's front axle vertical oscillations was 7.41 cm^2 (Figure 11).

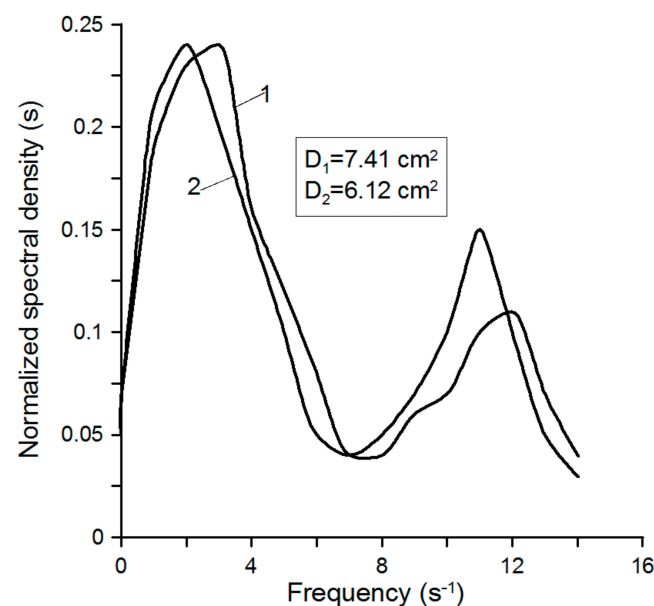


Figure 11. Normalized spectral densities of vertical oscillations of tractor's front axle with (1) and without (2) chopper.

In the absence of PRR-1.5, the value of this parameter was less and equal to 6.12 cm^2 . The ratio of these variances shows that the true value of the F-test is equal to 1.21. It is less than the F-test's table value, which for the significance level 0.05, is equal to 1.39. Hence, the null hypothesis of equality of the compared variances is not rejected and both represent the same general sample. Moreover, as follows from the analysis of Figure 11, the frequency composition of vertical oscillations of the tractor's front axle, both with and without PRR-1.5, is practically the same.

If the front chopper does not affect the tractor's vertical oscillations of the tractor's front axle, it should be expected that it will not affect the rear axle's vertical oscillations.

These oscillations depend on fluctuations of the surface's longitudinal profile and plough draft resistance. Later, this can affect the plowing depth stability.

The magnitude of connection between oscillations of the surface profile and the draft resistance of the plough, on the one hand, with oscillations of the plowing depth, on the other hand, can be easily estimated using the cross correlation functions. Their analysis shows that the plowing depth stability depends more on the oscillations of the surface's longitudinal profile (Figure 12, curve 1). In this case, the highest value of the cross correlation function is positive and equal to 0.75 (Figure 12, point A).

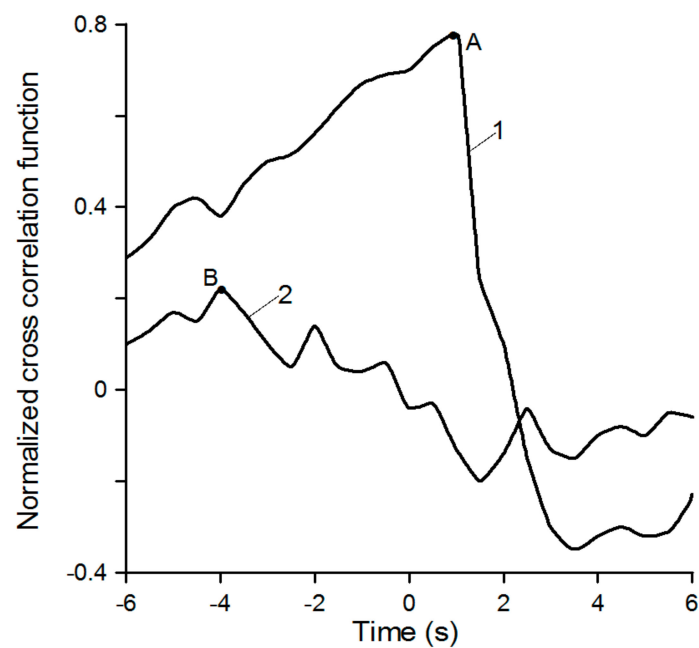


Figure 12. Cross correlation functions of plowing depth oscillations from the influence of the surface's longitudinal profile and plough draft resistance.

Additionally, this point is shifted to the right of zero vertical by 1 s. This is the time at which plowing depth oscillations (process 1) are late from oscillations of the surface's longitudinal profile (process 2). In this case, process 2 is a steering action.

Oscillations of the plow draft resistance had little effect on plowing depth oscillations. The maximum value of the cross-correlation function, emphasizing the relationship between these oscillations, is only 0.22 (Figure 12, point B). It is about 3.4 times less than for the function, reflecting the interconnection between oscillations of the plowing depth and the surface's longitudinal profile.

When the chopper's working devices were rotated with a 540 rpm portion of the sunflower stubble residues in length less than 15 cm, it was 41% (Table 3). The share of stubble residues 15–30 cm in length was approximately the same (43.4%). Unchopped sunflower stubble accounted for 4.5%.

Table 3. Chopping quality of sunflower stubble.

Rpm	Number of Stubble Residues (%)			Total Chopping (%)
	<15 cm	15–30 cm	>30 cm	
540	41.3	43.4	15.3	95.5
1000	63.5	32.7	3.8	99.0

After passing the plow-chopping unit, less than 1.5% of chopped stubble residues remained on the plowed field's soil surface.

An increase in the chopper's working devices' rotational speed to 1000 rpm increased the number of residues less than 15 cm in length by almost 1.5 times. The number of stubble particles more than 30 cm long decreased more than three times (from 15.3 to 3.8%). In this case, the unchopped part of the sunflower stubble was only 1%. After passing the plow-chopping unit with this PRR-1.5 arrangement, the chopped residues' incorporation into the soil was complete.

4. Conclusions

To reduce by two times the dynamic load in the drive of the working devices of the plant residues front chopper, their high-quality chopping, and subsequent covering with the soil, the tractor's frontal PTO must be adjusted to a speed of 1000 rpm.

Even though the tractor's front axle vertical oscillations variance when using a front chopper of plant residues increases from 6.12 to 7.41 cm², this gain is statistically random and insignificant.

The use of the plant residues frontal chopper does not impair the statistical characteristics of the plowing depth. Changing aperiodically in the frequency range of 0–2.5 Hz, the variance of its oscillations (1.44 cm²) is not randomly less than the variance of oscillations of the longitudinal field profile (2.75 cm²). Even smaller oscillations in the plowing depth depend on fluctuations in the arable-chopping unit's plow draft resistance.

This is evidenced by the small value of the cross-correlation function: for the oscillatory processes 'plow draft resistance—plowing depth' its value is equal to 0.22, which is 3.4 times less (0.75) than for the oscillatory processes 'field profile—plowing depth'.

The plant residues chopper's operation with a frequency of 1000 rpm increased the number of chopped particles by less than 15 cm in length by 1.5 times and reduced the number of those exceeding 30 cm in length by 3 times. This ensured their almost complete covering with the soil together with the uncut part of the sunflower stubble, which did not exceed 1%.

Author Contributions: Conceptualization, V.B. and V.A.; methodology, V.B., A.A., and V.N.; software, V.K. (Viktor Kaminskiy) and V.N.; validation, V.B., A.A., and V.K. (Volodymyr Kyurchev); formal analysis, V.A.; investigation, V.B. and V.K. (Volodymyr Kyurchev); resources, V.B.; data curation, V.N.; writing—original draft preparation, V.K. (Volodymyr Kyurchev) and V.N.; writing—review and editing, V.B. and A.A.; visualization, V.N. and V.K. (Viktor Kaminskiy); supervision, V.N.; project administration, V.B.; funding acquisition, H.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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