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TURNING RESEARCH OF A SOWING UNIT BASED ON REVERSIBLE TRACTOR

Pavol FINDURA[1], Katarína KOLLÁROVÁ[2], Volodymyr NADYKTO[3]*,
Volodymyr KYURCHEV[3], Ivan ZHOKIN[3]

[1]Slovak University of Agriculture in Nitra, Faculty of Engineering, Institute of Agricultural Engineering, Transport and Bioenergetics, Nitra; SUA University Farm in Kolíňany, Slovak Republic, pavol.findura@uniag.sk
[2]Slovak University of Agriculture in Nitra, Faculty of Engineering, Information and Coordination Centre of Research, Nitra, Slovak Republic, katarina.kollarova@uniag.sk
[3]Dmytro Motornyi Tavria State Agrotechnological University, Mechanical and Technological Faculty, Melitopol, Ukraine, volodymyr.kyurchev@tsatu.edu.ua (V.K.), zhokin.vanya@gmail.com (I.Z.)

*correspondence: volodymyr.nadykto@tsatu.edu.ua

Modern sowing machine-tractor units (MTU) can be divided into single-machine (single-module), two-machine (double-module), and three-machine (triple-module). The firsts, consisting of a tractor and a trailed/mounted seeder, are the most studied and, therefore, the most widespread. Two-module MTUs mainly use trailed or semi-mounted hitch and trailed seeders. The units of this type have been studied less. Three-module sowing complexes are even less common. Most are based on a trailed hitch and trailed seeders placed behind the tractor. There are samples of MTU with side-mounted seeding machines, but their knowledge is extremely insufficient. This paper examines a three-module MTU based on a tractor with reverse motion and a front semi-mounted hitch. One of the problems in using this sowing unit is the choice of design parameters that would ensure safe turning when manoeuvring on the headland. Theoretical and experimental studies have established that by increasing the side seeder's towbar length, MTU's safe turning under analysis with machines of a larger operating width can be performed with a smaller distance between their inner wheels and tractor's wheels (parameter *d*). If the coincidence condition of side seeders' wheel axes with the tractor wheels axe is met, an increase in the tractor track from 1.7 to 2.5 m allows for a decrease in the value of the distance d. This solution is especially effective when using seeders with an operating width of 3.6 m. In this case, the indicated decrease reaches a fivefold size, from 0.5 to 0.10 m. With the seeders' operating width of 5.4 m, the distance *d* can only be reduced by 1.4 times. But with this option for sowing MTU, it is possible to use a tractor with dual rear tyres and a parameter *d* value of 0.98 m. Actual oscillations in the distance *d* value within 0.28 ±0.01 m in the process of turning the studied sowing machine-tractor unit at a velocity of 2.2 $m \cdot s^{-1}$ are characterized by low variance ($0.64 \cdot 10^{-4}$ m^2) and low (no more than 1.75 Hz) frequency. This allows us to consider this MTU's mode movement on the headland quite safe.

Keywords: turn; headland; turning radius; manoeuvring; kinematic length of the unit

The challenges of Ukrainian farmers currently lie in treating large sown areas (from 500 to 5000 hectares) more efficiently. At first, this concerns significantly reducing the time spent on technological operations. Considering this, sowing machine-tractor units (MTU) are becoming wider. They often consist of several modules and are made in a trailed version. Due to their structural complexity, such sowing units are insufficiently researched and, therefore, insufficiently understood. This is especially true for their turning ability when manoeuvring on a headland. At the same time, according to research data, this unproductive process can take up to 20% of the sowing MTU's operating time (Yatskul et al., 2014).

Schematically, most sowing units can be divided into three groups:

1. single-machine (single-module);
2. two-machine (two-module);
3. three-machine (three-module).

Sowing complexes with more than three machines (modules) are extremely rare. Many of them are at the stage of their theoretical and experimental research.

It should be noted that the turning ability theory of single-module MTUs has been studied most fully. Moreover, the laws of their movement on the headland are similar to the units' movement ones for various technological purposes (Karkee and Steward, 2010; Szakács, 2010). Particular attention was given to the study of loops, loopless, and relatively complex reverse turns (Bochtis and Vougioukas, 2008; Boryga, 2023). Their implementation involves moving the units in reverse (Trendafilov, 2021). It is noted that such a manoeuvre requires high driver training. But, using the MTU reverse movement on the headland can significantly reduce its width (Cariou et al., 2010).

Research has established that clothoids are theoretically best suited for designing the optimal path of MTU movement on a headland (Sabelhaus et al., 2013). But calculations using them are quite complex and practically not used. Instead, curves with a constant radius of curvature are used (Khan et al., 2017). Using them, T. Oksanen and other researchers studied the issues of planning manoeuvres during an agricultural operation. Their proposed algorithm is based on enumerating possible combinations of unit movement on the headland (Oksanen, 2007; Oksanen and Visala, 2004; Vougioukas et al., 2006).

As a result of the research (Belyaev et al., 2022), an experimental factorial static mathematical model was obtained as an analytical relationship that determines the trajectory of a wheeled vehicle along a deformed base on a headland. This model makes it possible to evaluate the kinematic and dynamic characteristics of a sowing MTU depending on such design and operational parameters as travel velocity, the tractor's longitudinal wheelbase and track width, the turning angle of its steering wheels, etc.

Belyaev et al. (2017) assessed the quality of the work of various sowing complexes. But they are all single-module trailed machine-tractor units with different operating widths. Frames with a large value of this design parameter are made hinged. This allows them to better copy the unevenness of field oscillations in the transverse direction.

Two-module sowing units are less common in practice, so the kinematics and especially the dynamics of their movement on the headland have been studied much less. Quite often, the modules of such a unit are not arranged in a line but sequentially, one after another (Li et al., 2015; Talarczyk et al., 2016; Tu and Tang, 2019). As a result, the MTU has a considerable kinematic length and relatively low manoeuvrability. Because of this, reverse turns are practically impossible for them.

Publications are devoted to studying two-module sowing MTUs based on a semi-mounted hitch (Bulgakov et al., 2018; Ivanovs et al., 2018). The movement dynamics of these units on the headland were studied using the principles set out by Bulgakov et al. (2016). Researchers have found that using a semi-mounted hitch instead of a trailed one makes two-module sowing units more manoeuvrable and productive.

Three-module sowing MTUs are even less common in practice. The three seeders are usually located behind the tractor and attached using a trailed hitch (Fig. 1).

The main disadvantages of such MTUs are their considerable kinematic length and significant turning radius. Because of this, a relatively large headland width is required, and substantial time is required to complete the turn. Ultimately, all this leads to an increase in unproductive time.

It should also be noted that specific research in solving problems for such sowing machine-tractor units is insufficient. Available examples demonstrate the technical and economic efficiency of three-module MTUs designed using semi-mounted attachment devices (Konstantinov and Terpilovsky, 2006). Moreover, both with the rear rank and the machines' lateral arrangement concerning the tractor. A bridge circuit connecting three seeders with two tractors was also evaluated. However, no studies concerning kinematics, and such MTUs' turning dynamics are practically absent. This makes it very problematic to resolve the issue of their design parameters' justified choice.

In practice, a three-module unit is used for mowing grass into windrows. It comprises a self-propelled vehicle, a front mower, and two side mowers (Antille et al., 2019). However, the results of the studies on kinematics or dynamics, both during working movement and when turning, were not found in the information sources.

Krasovskikh et al. (2012) describe the design of a three-module sowing complex with a side arrangement of two mounted seeders. At the same time, the sowing machines are located close to the front. However, the authors describe only the design of the unit. They do not consider the kinematics or the dynamics of its movement on the headland.

We have developed a three-module sowing unit consisting of a tractor configured for reverse movement, a semi-mounted hitch, and trailed seeders. Moreover, two of them are lateral, and one is central. Side-trailed seeders are attached to a hitch, which is attached to the tractor's three-point rear linkage system. When the tractor moves

Fig. 1 Three-machine (three-module) trailed sowing machine-tractor unit

in reverse, its linkage system, together with the hitch and two seeders, is the front one. The third trailed grain seeder is attached to the tractor's front linkage system, which, in this case, is located at the rear. As a result, a compact sowing unit of a new design is formed, characterized by a relatively small kinematic length with a relatively large operating width.

However, in the process of turning such an MTU, there is a possibility of collision of the front side seeders' wheels with the tractor's wheels. In this regard, the aim of these studies was: i) theoretically select such parameters of the sowing unit that would prevent the side seeders wheels from touching the wheels of a reverse-tuned tractor when moving on the headland; ii) practically assess the reliability of the safe turn of the new three-module MTU; and iii) give practical recommendations on the choice of design parameters of a three-module sowing unit based on a tractor with reverse motion.

Theoretical premises

The diagram of a three-module unit based on a reversibly configured tractor, a semi-mounted hitch and three trailed seeders is shown in Fig. 2. When such an MTU moves in a straight line, the rear wheels of the tractor located in front are non-steering. The wheels of the side seeders are situated at a distance *d* from them. To avoid their collision with the tractor wheels when turning the unit, the value of parameter *d* must be such that the following condition is met (see Fig. 2):

$$OC < OT \tag{1}$$

In this equation, OC is the distance from the attachment point of the seeder to the hitch frame (point O), to point C located on the seeder wheel; OT is the distance from the specified point O to point D located on the tractor wheel.

From triangle ODC, we find that:

$$OC = \sqrt{OD^2 + DC^2} = \sqrt{(l_s + r_s)^2 + \left(\frac{B_s}{2} + s\right)^2} \tag{2}$$

where: l_s – distance from the axis of the seeder wheels to the point of its attachment to the hitch (m); r_s – radius of the seeder wheels (m); B_s – seeder operating width (m); s – seeder's wheel tyre width (m)

We find the distance OT from the triangle OTM:

$$OT = \sqrt{MT^2 + OM^2} = \sqrt{l_o^2 + \left(\frac{B_o - B - b}{2}\right)^2} \tag{3}$$

where: l_o – distance from the tractor wheel to the hitch frame (m); B_o – distance between the attachment points of the side seeders to the hitch frame (m); B, b – track and tractor's wheel tyre width (m)

Analysing Fig. 2, the value of the B_o parameter can be determined from the equation:

$$B_o = B + b + 2d + 2s + B_s \tag{4}$$

Taking into account Eq. (4), Eq. (3) is transformed to the following form:

$$OT = \sqrt{l_o^2 + \left(d + s + \frac{B_s}{2}\right)^2} \tag{5}$$

Substituting Eqs (2) and (5) into (1), after carrying out the appropriate transformations, we finally obtain:

$$d > \sqrt{(l_s + r_s)^2 + \left(\frac{B_s}{2} + s\right)^2 - l_o^2} - s - \frac{B_s}{2} \tag{6}$$

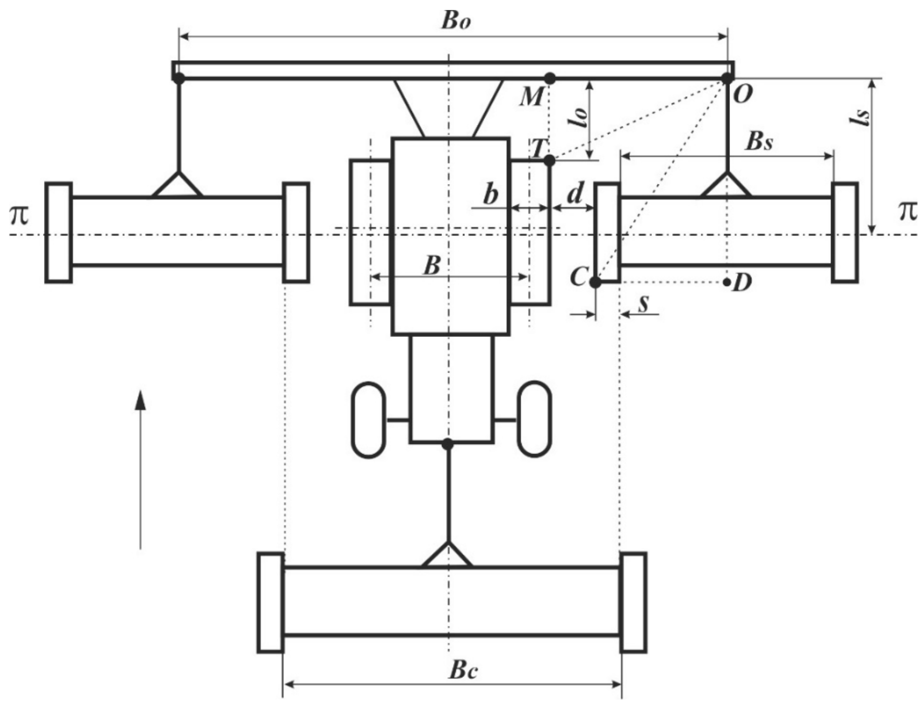

Fig. 2 Diagram of machine-tractor unit's movement

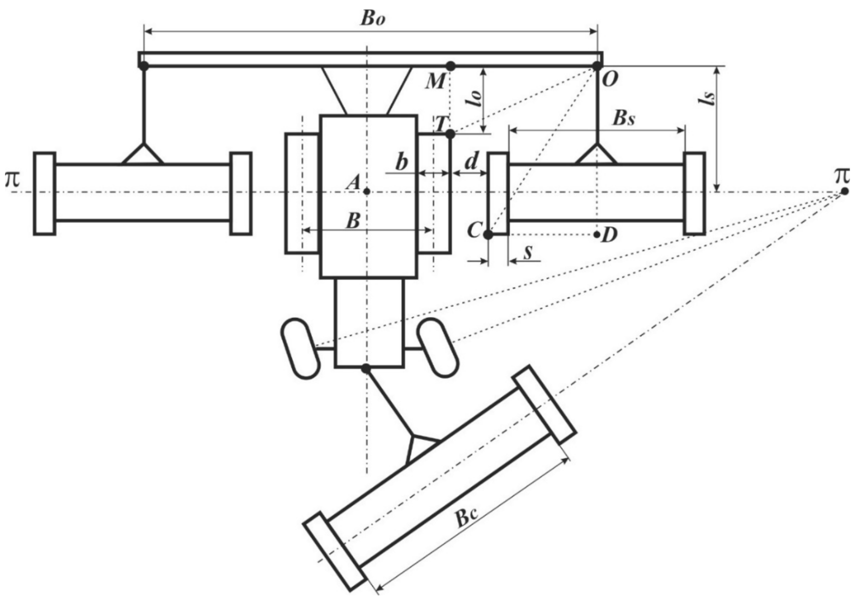

Fig. 3 Diagram of machine-tractor unit's turning

Equation (6) does not include the operating width of the central seeder (B_c). In general, the value of this parameter can be different from the operating width of the side sowing machines (B_s). As follows from the analysis of Fig. 2, the value of the B_c parameter can be determined from the equation:

$$B_c = B + b + 2s + 2d \qquad (7)$$

If the width of all seeders of the sowing unit is the same (i.e. $B_c = B_s$), then from Eq. (4), taking into account Eq. (7), we obtain an utterly logical result in the form

$$B_o = 2B_s \qquad (8)$$

It should be noted that a safe turn of the MTU under consideration can be achieved without fulfilling the requirement (6). To do this, it is necessary to ensure a condition under which the axes of the tractor wheels and side seeders ones would be on the same line (π–π, Fig. 3). This condition will be met when:

$$l_s = l_o + R \qquad (9)$$

where: R – tractor's rear wheels radius (m)

With this attachment, the side seeders (like physical pendulums) in the process of turning the MTU can perform some angular oscillations relative to the points of their attachment to the hitch (point O, Fig. 3). But with an appropriate selection of the parameter d value, these oscillations will not be able to cause the wheels of the side seeders and the tractor to touch.

The analysis of Fig. 3 shows that this value of parameter d can be determined from the following equation:

$$\frac{B_o}{2} = \frac{B}{2} + \frac{b}{2} + \frac{B_s}{2} + d + s \qquad (10)$$

Taking into account Eq. (8), from Eq. (10) we finally obtain:

$$d = \frac{B_s - B - b - 2s}{2} \qquad (11)$$

The value of parameter d calculated using Eq. (11) is relatively easy to check in natural (field) operating conditions of this three-module MTU.

Fig. 4 KhTZ-160 with three C3-3,6 seeders

Table 1 Technical characteristics of a three-module sowing unit

Index	Symbol	Value
KhTZ-160 tractor		
Tyre size	16.9R38	–
Wheel track	B (m)	2.10
Tyre width	b (m)	0.43
Tyre radius	R (m)	0.77
Minimum turning radius	R_m (m)	6.15
SZ-3.6 seeder		
Operating width	B_s (m)	3.60
Tyre width	s (m)	0.24
Tyre radius	r_s (m)	0.57
Trailer hitch length	l_s (m)	2.15
SN-75 attachment device:		
Operating width	B_o (m)	7.20
Connecting size	l_o (m)	0.98

Material and methods

The physical object of research was a sowing unit (Fig. 4) consisting of a KhTZ-160 tractor (Ukraine), a semi-mounted SN-75 hitch, and three trailed CZ-3.6 seeders (Elvorti, Ukraine). The tractor was configured for reverse driving mode. The dimensional characteristics of the unit used for theoretical calculations are presented in Table 1.

The theoretical cycle of research consisted of two stages. The first of them is the dependence of the distance d and the operating width of the central seeder B_c on changes in the parameters l_s, B_s, and l_o. For this purpose, Eqs (6) and (7) were used. At the same time, in addition to the SZ-3.6 seeders, we considered the fairly common similar machines SZ-5.4 with an operating width of 5.4 m.

The second stage of the research consisted of determining the parameter d when setting up the sowing unit according to Eq. (9). The value of the safe distance d calculated by Eq. (11) was used to check the adequacy of its value in field conditions. To do this, we studied the right-hand turn on of a three-module sowing unit (Fig. 4) at the maximum turning angle of the tractor steering wheels. This ensured the curvilinear movement of the MTU under study on the headland with a minimum turning radius $R_m = \pi A$ (Fig. 3).

Sowing unit turning was carried out on a fallow. Its background made it possible to obtain a clear trace of the movement of tractor and seeder wheels. During the movement and after turning the unit through an angle of no less than 270°, the following parameters were measured in triplicate:

1. the distance between the centres of the tracks (parameter d) left by the right wheel of the tractor and the left wheel of the right seeder;
2. the diameter of the semicircle (D) formed by the track of the tractor's right wheel;
3. time (t) for the tractor to turn 180°.

The parameter d was measured every 20 cm. For this purpose, a ruler with a measurement accuracy of ±1 cm was used. A Stanley Longtape (France) precision class II tape measure with a length of 20 m was used to measure the parameter D. The time it took the sowing unit to pass the semicircle was measured using an electronic stopwatch KHP PC3860 (China) with a measurement error of 0.01 s.

Based on the results of distance measurements d, the following were calculated:

1. the mean value;
2. variance;
3. the coefficient of variation;
4. normalized correlation function;
5. normalized spectral density.

The mean values of the parameters D and t were used to calculate the turning velocity (V, m·s^{-1}) of the studied sowing unit:

$$V = \frac{\pi(D+B)}{2 \cdot t} \tag{12}$$

It should be noted that the value $\frac{(D + B)}{2} = R_{min}$ represents the actual value of the MTU's minimum turning radius.

Results and discussion

The analysis of the calculation results shows that an increase in the value of the design parameter l_s (see Fig. 3)

Table 2 Influence of the l_s parameter on the sowing unit parameters

Parameter l_s (m)	Parameter d (m)		Parameter B_c (m)	
	seeder operating width B_s			
	B_s = 3.6 m	B_s = 5.6 m	B_s = 3.6 m	B_s = 5.6 m
1.85	1.00	0.8	5.0	4.6
2.00	1.15	0.9	5.3	4.8
2.15	1.30	1.0	5.6	5.0
2.30	1.45	1.1	5.9	5.2
2.45	1.60	1.2	6.2	5.4

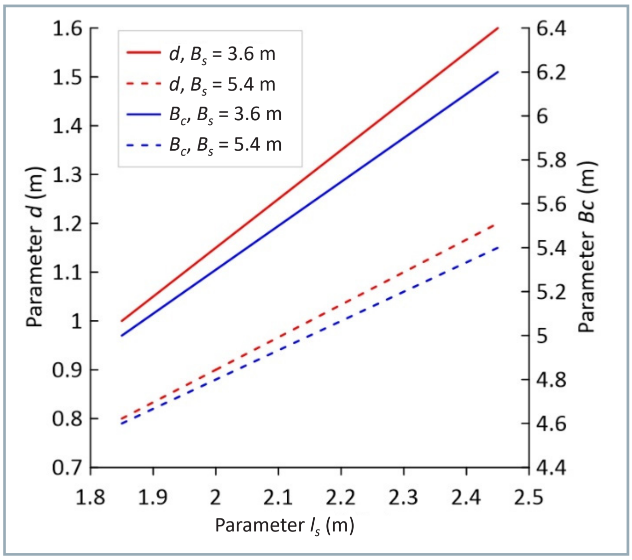

Fig. 5 Dependence of the parameters d and B_c on the value of l_s parameter for different operating widths of side seeders (B_s)

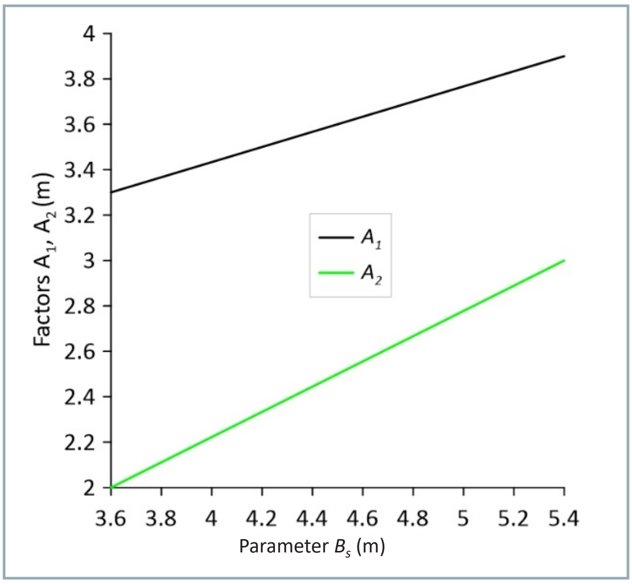

Fig. 6 Changes in the A_1 and A_2 factors depending on the operating width of the side seeder (B_s)

requires an increase in the value of the parameter d (Table 2).

Moreover (Fig. 5), both when using SZ-3.6 seeders (red solid line) and SZ-5.4 seeders (red dotted line).

However, when using the latter (that is, wider seeders), a significantly smaller value of distance d is required. Namely, at l_s = 1.85 m, the value of d is less by 0.2 m, and at l_s = 2.45 m – by 0.4 m. To explain this result, let us present the analytical equation (6) in the following form:

$$d = A_1 - A_2 \quad (13)$$

where:

$$A_1 = \sqrt{(l_s + r_s)^2 + \left(\frac{B_s}{2} + s\right)^2 - l_o^2}$$

$$A_2 = s + \frac{B_s}{2}$$

Next, by changing the value of the parameter B_s, we will evaluate its influence on the nature of the change in A_1 and A_2 factors. The analysis of the results obtained shows (Fig. 6) that with increasing seeder operating width (B_s), the values of both factors also increase. But the intensity of their growth is different: for the A_2 factor it is higher. As a result, as the B_s parameter increases, the difference in the values of A_1 and A_2 factors (that is, parameter d) becomes smaller. It follows from this that with an increase in the value of the design parameter l_s, the safe turning of the studied MTU with the seeders of a larger operating width (B_s) can be performed with a smaller distance value between their inner wheels and the tractor's wheels (parameter d).

The operating width of the central seeder increases as the value of the l_s parameter increases when using seeding machines with B_s = 3.6 m (solid blue line, Fig. 5) and when using machines with B_s = 5.4 m (dashed blue line). This result is quite logical if we analyse Eq. (6) analytically.

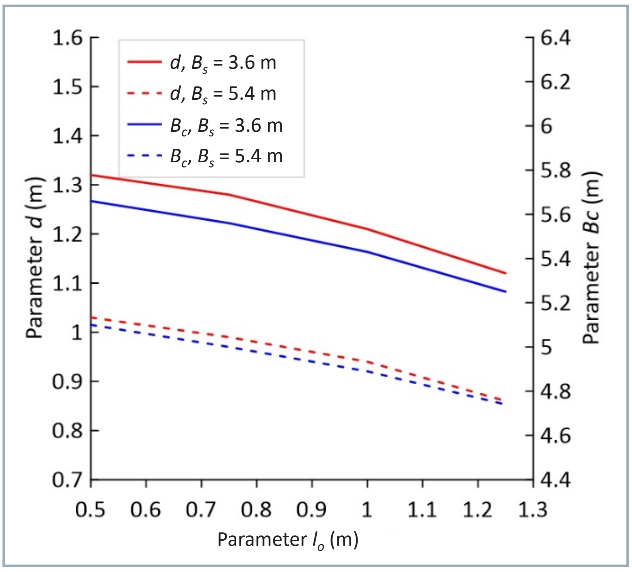

Fig. 7 Dependence of d and B_c parameters on the value of l_o parameter for different operating widths of side seeders (B_s)

At the same time, increasing the value of the design parameter l_o (see Fig. 3) from 0.5 to 1.5 m requires decreasing the value of the distance d (Table 3).

From an analytical point of view, such a result, as follows from the analysis of Eq. (6) and Fig. 7, is natural. From a design point of view, increasing the value of the l_o parameter slightly increases the longitudinal dimension of the seeding MTU, which is undesirable. It follows that the actual value of l_o should be taken as the one provided when the hitch is directly connected to the tractor's linkage links.

Equation (11), as noted above, allows us to determine the value of the parameter d if condition (9) is met. Calculations show that increasing the tractor track (B) from 1.7 to 2.5 m allows for a decrease in the distance d. This

Table 3 Influence of the l_o parameter on the sowing unit parameters

Parameter l_s (m)	Parameter *d* (m)		Parameter B_c (m)	
	seeder operating width B_s			
	B_s = 3.6 m	B_s = 5.6 m	B_s = 3.6 m	B_s = 5.6 m
0.50	1.32	1.03	5.66	5.1
0.75	1.28	0.99	5.56	5.0
1.00	1.21	0.94	5.43	4.89
1.25	1.12	0.86	5.25	4.74

solution is especially effective when using seeders with an operating width of 3.6 m. In this case, the indicated reduction reaches a fivefold size, from 0.5 to 0.10 m (Fig. 8).

With a seeders' operating width of 5.4 m, the distance *d* can only be reduced by 1.4 times (red dashed line, Fig. 8). But with this version of the sowing MTU, it is quite possible to use a tractor with dual rear tyres (*b* = 0.86 m). With a seeders' operating width of 5.4 m, the distance *d* can only be reduced by 1.4 times (red dashed line, Fig. 8).

A three-module sowing unit with seeders with an operating width of 3.6 m was used to study this process experimentally. This MTU has l_o = 0.98 m. With the tractor wheel radius *R* = 0.77 m, the l_s parameter value, as follows from Eq. (9), should be equal to 1.75 m. Since the SZ-3.6 seeder has an l_s parameter equal to 2.15 m, then per condition (9), the attachment point of the side machine to the hitch was moved forward by 0.4 m (see Fig. 4).

With the tractor track *B* = 2.1 m, the tyre width of its wheels *b* = 0.43 m, the tyre width of the seeders wheels *s* = 0.24 m and their operating width B_s = 3.6 m, the calculated value of parameter *d*, as follows from Eq. (11), was 0.295 m (point A, Fig. 8). In a natural sowing unit, this distance was taken to be 0.30 m.

On the headland, the three-module sowing unit moved at a velocity the mean value of which was relatively high and was 2.2 m·s^{-1}. The MTU's minimum turning radius value was R_{min} = 6.22 m. This is 0.07 m more than its passport value of 6.15 m (see Table 1).

As follows from the experimental data analysis, the mean value of the distance between the wheels of the tractor and the side seeder (parameter *d*) varied within 0.28 ±0.01 m. The oscillations variance of this parameter was 0.64·10^{-4} m^2 (that is, 0.64 cm^2), and the coefficient of variation was 2.9%. If we consider that the latter's value does not exceed 10%, then the oscillations process of the parameter *d* is regarded as low-variable (Dospekhov, 1985). Correlation-spectral analysis data support this fact.

As follows from the nature of the change in the normalized correlation function (Fig. 9), the correlation length between the measurements of the parameter *d* is equal to 1.5 m. In principle, the oscillatory process being studied contains some hidden periodic component. However, judging by the variance of the process, it is characterized by an insignificant amplitude.

The analysis of the normalized spectral density shows that the main part of the variance in the oscillations of the parameter *d* is concentrated in a relatively narrow frequency range equal to 0–5 m^{-1} (Fig. 10). At a seeding unit velocity of 2.2 m·s^{-1}, this amounts to 0–11 s or 1.75 Hz.

The maximum value of spectral density occurs at a frequency of 1 m^{-1}. At the mentioned seeding unit velocity, this equals 2.2 s or only 0.35 Hz.

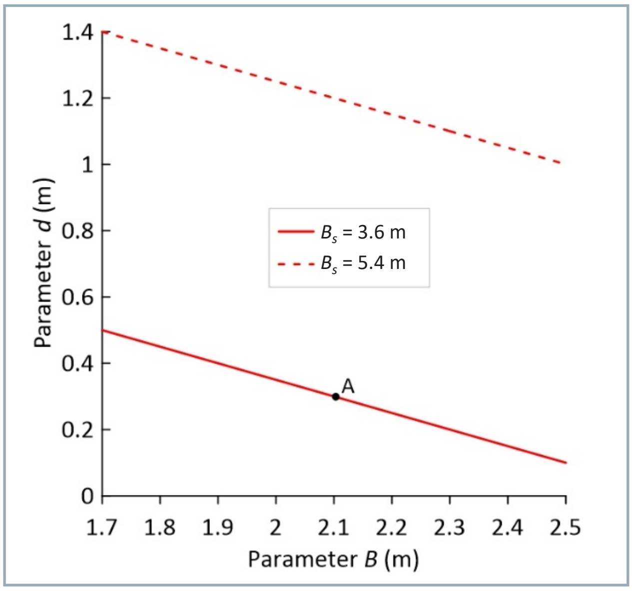

Fig. 8 Dependence of parameter *d* on tractor track (*B*) at different values of seeder's operating width (B_s)

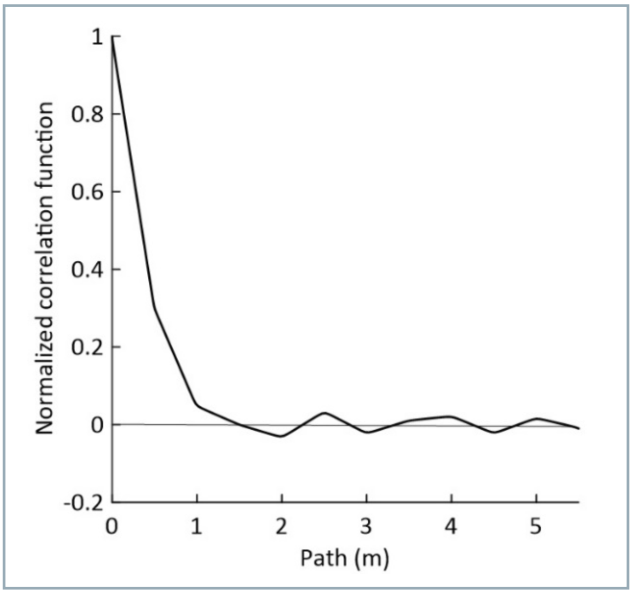

Fig. 9 Normalized correlation function of parameter *d* oscillations

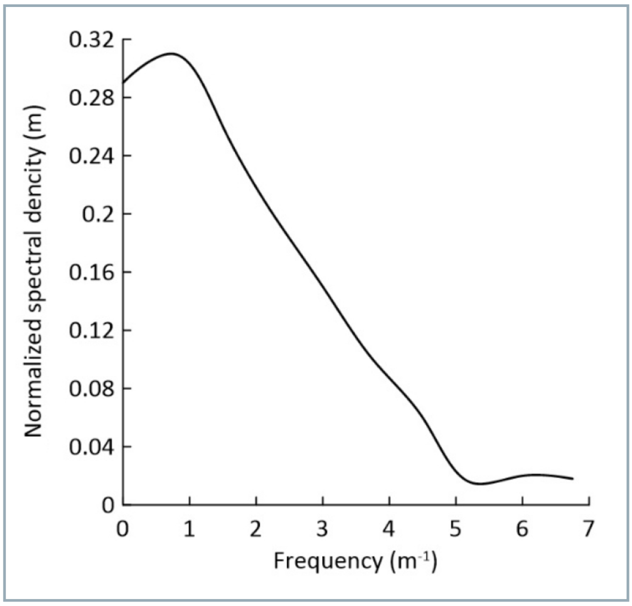

Fig. 10 Normalized spectral density of parameter *d* oscillations

The above correlation-spectral analysis clearly shows that oscillations in the value of distance *d* within 0.28 ±0.01 m during the studied machine-tractor unit turning are characterized by low dispersion and low frequency. This mode of MTU movement on the headland is considered entirely safe.

Moreover, the turn performed by the unit under study is safe and kinematically correct. The latter, when manoeuvring one or another machine-transport unit on the headland, occurs provided that (see Fig. 3):

$$\frac{B}{2}+\frac{b}{2}+d+2s+B_s<R_{\min} \quad (14)$$

In our case, when $B = 2.1$ m; $b = 0.43$ m; $d = 0.28 \pm 0.01$ m; $s = 0.24$ m; and $B_s = 3.6$ m, condition (14) is met.

Conclusion

As a result of theoretical studies, analytical dependencies have been derived that make it possible to evaluate the influence of the three-module sowing unit design parameter with a reversible tractor on the possibility of making a safe and correct turn with a minimum radius. The analysis of these dependencies showed that:

- with an increase in the length of the seeder's towbar (parameter l_s), the safe turning of the test MTA with the machines of a larger operating width can be performed with a smaller distance between their inner wheels and the wheels of the tractor (parameter *d*);
- increasing the distance from the hitch frame to the tractor wheel (parameter l_o), although it allows reducing the value of parameter *d*, but leads to an undesirable increase in the longitudinal dimension of the sowing MTU;
- provided that the condition of the wheel axes of the side seeders coincides with the tractor wheels' axe, an increase in its track from 1.7 to 2.5 m allows for a decrease in the value of distance *d*. This solution is especially effective when using seeders with an operating width of 3.6 m. In this case, the indicated decrease reaches a fivefold size, from 0.5 to 0.10 m. With a seeders' operating width of 5.4 m, the distance *d* can only be reduced by 1.4 times. However, with this option for sowing MTU, it is quite possible to use a tractor with dual rear tyres and a parameter *d* value of 0.98 m.

From the experimentally obtained correlation-spectral analysis, it clearly follows that oscillations in the value of distance *d* within 0.28 ±0.01 m during the turning of the studied sowing machine-tractor unit at a speed of 2.2 $m \cdot s^{-1}$ are characterized by low variance ($0.64 \cdot 10^{-4}$ m^2) and low (no more than 1.75 Hz) frequency. This allows us to consider this MTU's movement mode on the headland quite safe.

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