# INVESTIGATION OF WIDE SPAN VEHICLE TECHNOLOGICAL PART MOVEMENT STABILITY

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**Abstract.** While driving a Wide Span Vehicle, depending on the conditions of its operation, the stability of movement of the agricultural machines, attached to it, may grow worse. Despite sufficient and thorough scientific research into the functioning of the mounted and semi-mounted agricultural machines on the mounted mechanisms of traditional tractors, the conditions for the stability of their movement on Wide Span Vehicles were not considered. Stable movement of an agricultural machine, coupled with a Wide Span Vehicle in the working position, can be ensured only on the basis of a correct choice of the design parameters of the mounted mechanism and the layout of the machine itself on it. However, scientists have not studied the effect of different schemes for connecting agricultural vehicles to the Wide Span Vehicle on the stability of their movement. The purpose of this research is to study the process of functioning of mounted agricultural machines on Wide Span Vehicles to ensure sufficient stability of movement from the position of satisfactory angular mobility of its technological part. Theoretical investigations, synthesis of the design schemes and parameters of the Wide Span Vehicle were carried out by modeling on a PC the conditions of its operation, using the basic principles of theoretical mechanics, tractor theory and the theory of automatic control of linear dynamic systems while reproducing statistically random control and disturbing input impacts. Experimental studies were performed, using both generally accepted and developed methods, and included use of modern control and measuring equipment. Processing of the experimental data took place on a PC, using a regression analysis. The physical object of the experimental research was a Wide Span Vehicle. As a result of the research, it was found that from the position of a more stable movement of the technological part of the Wide Span Vehicle (less vibrations), the advantage is given to the arrangement of an agricultural implement on a mounted mechanism behind the axis of its attachment since the dispersion of vibrations of the implement in this case is 33% less than in its variant of placement in front of its mounting axis. These oscillations are of low-frequency and constitute a spectrum of 0…0.16 Hz. Oscillations of the mounted mechanism of the Wide Span Vehicle in the option of placing an agricultural implement on the mounted mechanism in front of the suspension axis should be considered as a disturbing effect on the straight-line movement of the Wide Span Vehicle, and as a consequence an undesirable reaction and its undesirable rotation in one direction or another.

**Keywords:** wide span vehicle, stability of movement, technological part, mounted mechanism, experimental investigations.

## Introduction

A perspective direction of further development of agriculture in the world is the introduction of Controlled Traffic Farming (CTF) [1; 2]. When implementing the basic principles of CTF, the greatest effect can be achieved through the use of Wide Span Vehicles (WSV) [3; 4], which move along the tracks of a constant tramline, located at a step, equal to its span. In the area between the tramline tracks, there are placed agricultural machines, aggregated with WSV [5; 6].

When driving WSV or a traditional tractor, depending on the conditions of their operation, the stability of movement of agricultural machines, aggregated with them, may deteriorate [7; 8]. Investigations [9] proved that this occurs due to insufficient angular mobility of the agricultural machines in relation to the source of energy. In order to ensure sufficient angular mobility of the mounted agricultural machines, aggregated with WSV or a traditional tractor, the design of its mounted mechanism must ensure a possibility of their independent rotation in a horizontal plane [10]. To do this, in practice the lower links of the rear suspension mechanism of the traditional tractor are installed not parallel, but at a certain angle of convergence [11].

When choosing a scheme for aggregating agricultural machines with WSV, the option of articulated connection to it prevails [12]. The choice of such a design solution can be explained by the fact that, when encountering a mechanical obstacle, the working body of the agricultural machine can deviate aside and prevent its damage.

Practical experience in using WSV has shown that of all the considered schemes for connecting the mounted and semi-mounted agricultural machines to them, two were found to be the most efficient [4; 12]. According to the first scheme, the working part on the WSV suspension mechanism is placed behind the suspension axis, but the second – in front.

At the same time, by well-known investigations of the work of the traditional machine-tractor aggregates it has been proved that, in order to ensure stable movement of a mounted machine, the instantaneous centre of rotation of the mechanism, mounted on the tractor, must be located behind the suspension axis [13]. However, even if this condition is met, the scheme of placing an agricultural machine on a mounted mechanism behind the suspension axis has significant advantages over the scheme in which the machine is placed in front of the suspension axis. First of all, because the agricultural machine, when it is aggregated with a means of energy, in the first option of placing it on the mounted mechanism is actually in the traction mode, in contrast to the second option, in which it is in the pushing mode. And a body that is in the traction mode is essentially a physical pendulum, the stability of its oscillations is practically asymptotic in nature.

Under real operating conditions of WSV through the wide wheelbase without artificially limiting the angular mobility of an agricultural machine in the horizontal plane, external disturbances will sooner or later force them to deviate by a critical value, and thereby lose control of their movement. Therefore, in order the movement of the hinged agricultural machine be stable, the WSV mounted mechanism should be deprived of excessive mobility in a horizontal plane. This result can be achieved only by correct choice of the scheme for connecting the agricultural machine to WSV and the parameters of its attachment mechanism, which is the subject of topicality of these investigations.

The results of theoretical studies of functioning of a frontally mounted mechanism on the tractor show that sufficient stability of the agricultural machine is possible only if it deviates from the longitudinal axis of symmetry by an angle not exceeding 1 deg [14]. Yet, under real operating conditions of a traditional machine-tractor aggregate, it is practically impossible to achieve such a result since the actual angle of rotation of the agricultural machine will be much greater.

A research that deserves certain attention comes to a conclusion that, in order to increase stability of the movement of an agricultural machine, frontally mounted on a tractor, its working parts should be arranged in the shape of a wedge [14]. But under real operating conditions such a law of motion of a frontally mounted implement is possible only when it is mounted in the traction mode, and not in the pushing mode. Otherwise, the mounted implement must have a limiter on its mobility in a horizontal plane.

Another group of scientists argues that the stability of movement of agricultural implements, operating in a pushing mode, can be ensured by improving their mechatronic systems [15; 16] or by introducing elastic elements into the design of the tractor mounted mechanisms. However, such a solution of the design will somewhat improve the mobility of a mounted agricultural machine on the mounted mechanism of the power tool but will not solve it at all. Only with significant rigidity of the elastic elements can one achieve critical deviation of the agricultural machine from the direction of movement of the aggregate. But in this case it is more advisable to consider the option of rigidly connecting an agricultural implement to a source of energy. If the result is positive, this will be a much cheaper solution of the design than complicating the attachment mechanism of the source of energy power with a system of elastic elements.

Despite sufficient and thorough scientific studies of operation of the mounted and semi-mounted agricultural machines on the mounted mechanisms of traditional tractors, the conditions for the stability of their movement on WSV have not been considered. But this issue requires study since the stable position of an agricultural machine, aggregated with WSV, can be ensured in the working position only on the basis of a correct choice of the design parameters of the mounted mechanism and the layout of the machine itself on it [17]. In addition, scientists have not studied the influence of different schemes of connecting the agricultural vehicles to WSV on the stability of their movement.

The purpose of the research is to study the process of operation of the mounted agricultural machines to WSV to ensure their sufficient stability of movement from a position of satisfactory angular mobility of its technological part.

The object of the research is the process of operation of WSV and mounted and semi-mounted agricultural machines, aggregated with it in a horizontal plane.

The subject of the research are the regularities of the impact of the aggregation scheme of mounted agricultural machines with WSV, and the parameters of the mounted mechanism upon the stability of its movement.

**Materials and methods**

The experimental investigations were carried out in a specially equipped laboratory for testing WSV (Fig. 1). The physical object of research was WSV, which was aggregated with a mounted soil-cultivating agricultural implement (Fig. 1).

Fig. 1. **Experimental prototype of WSV**

The agricultural tillage implement was attached to the mounted mechanism of the experimental WSV according to two schemes (Fig. 2), which differed in their placement relative to the axis of its mounting.

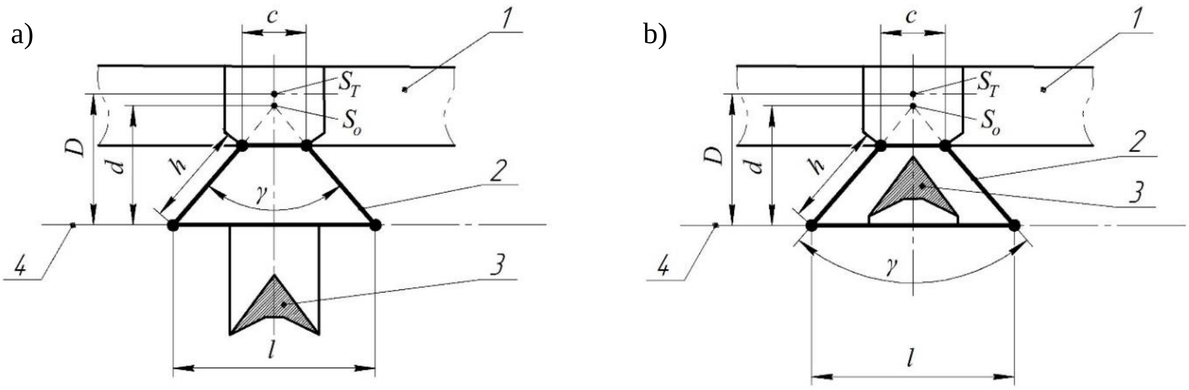


Fig. 2. **Schemes for placing a tillage implement on the WSV mounted mechanism in the variants behind the suspension axis (a) and in front of the suspension axis (b):** 1 – span beam WSV; 2 – mounted mechanism WSV; 3 – tillage implement; 4 – implement suspension axis

To measure the angle of rotation of the lower links of the rear linkage of WSV in the horizontal plane, we used an SP-3A rheochord sensor, which was mounted on the lower shaft of the WSV linkage, using a special device. When the lower link of the mounted mechanism was turned, the rotor stator rotated through the metal lead in contact with it, and its resistance changed accordingly. The signal from the slider was transmitted to the analog-to-digital converter. Calibration of the SP-3A rheochord sensor was performed using a specially developed angular scale-indicator. The calibration error of the SP-3A sensor was 10%.

Random processes of the angular directional mobility of WSV, the links of its mounted mechanism and other studied parameters of its functioning during the research were assessed by the frequency correlation-spectral characteristics.

The characteristics of the structure of random processes of the studied functioning parameters of WSV and its mechanisms are given by the normalized correlation function *ρ(τ)*, which shows the length of the correlation connection of the parameter being studied, what fluctuations predominate in this process, what its internal structure is [18]:

$$\rho(\tau) = \frac{1}{D_\tau(n-m)} \sum_{i=1}^{n-m} (\tau_i - T_\tau) \cdot \left(\tau_{i+m} - T_\tau\right) \quad , \tag{1}$$

where $n$ – number of measurements;
$m$ – number of correlation function points, $m = 0, 1, 2, \ldots$;
$\tau_i$ – value of the parameter to be studied, $i = 1, m$;
$T_\tau$ – mathematical expectation of the value of the parameter to be studied;
$D_\tau$ – dispersion of the parameter to be studied.

Another characteristic of the random stationary process of the studied parameters was the normalized spectral density $s(\omega)$. It describes the distribution of variances of the values of the studied parameters by frequency and gives an idea of the continuous spectrum of the frequencies that make up the random function [18]:

$$s(\omega) = \frac{\Delta\tau}{\pi} \cdot \; 1 + 2 \sum_{i=1}^{m} \rho_i(\tau) \cdot cos(\tau_i \cdot \Delta\omega) \Big] \; , \tag{2}$$

where $\Delta\omega = \pi \cdot (m \cdot \Delta\tau)^{-1}$ – frequency step of the parameter under study.

The methodology for calculating the correlation function and spectral density is described in [18]. To study the process of angular mobility in a horizontal plane of the mounted agricultural machines, aggregated with WSV, it is enough to consider a simplified equivalent diagram of the plane-parallel rotation of WSV and its mounted mechanism (Fig. 3)'. At the same time, we take into account that the nature of the disturbances fully depends on the design scheme of the WSV and its technological purpose.

In view of what was said above, let us assume that the WSV performs a uniform translational movement while moving relative to the stationary horizontal plane $xS_{Ty}$ (Fig. 3). As the WSV is moving, its skeleton under the impact of random disturbances deviates from its original position and receives additional speeds. As a result of this, relative movement of the WSV, starts with respect to the $xS_{Ty}$ plane. In addition, the plane, associated with the centre of mass of the WSV, rotates it around an axis, passing through its centre of mass (point $S_T$)). The measure of the WSV rotation is the heading angle $\varphi$, constructed by its longitudinal axis and the $S_{Ty}$ axis. Besides this, the lower links of its mounted mechanism also rotate; the measure of their rotation is angle $\beta$ (Fig. 3).

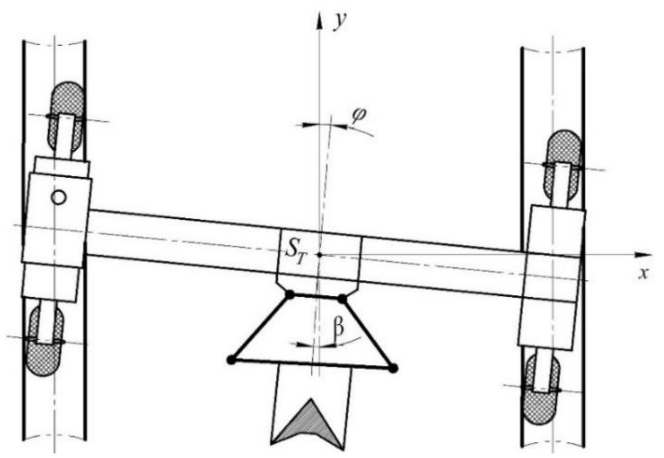


Fig. 3. **Diagram of angular mobility of WSV and the lower links of its mounted mechanism in a horizontal plane**

From the standpoint of sustainable movement of the agricultural machines, aggregated with WSV, it is of interest to study the nature of interdependent oscillations in a horizontal plane of the heading angle $\varphi$ of WSV and the angle $\beta$ of rotation of its mounted mechanism in different options of placing the agricultural implement on it, relative to the suspension axis (see Fig. 2).

To ensure sufficient angular mobility of an agricultural implement, the design of WSV must have such angle $\gamma$ of convergence of the lower links of its mounted mechanism, at which the instantaneous centre of rotation will be in the area of the centre of mass of WSV [19]. In practice, this can be achieved by setting the required value from the distance between the lower link fastenings on the mounted mechanism (see Fig. 2). Such a position of the instantaneous centre of rotation of the WSV mounted mechanism is determined by the ratio of its design parameters $d$ and $D$ (see Fig. 2). These parameters determine the distances from the axis, passing through the attachment points of the lower links of the mounted mechanism to the instantaneous centre of rotation (point $S_0$) and the centre of mass (point $S_T$) WSV. If the parameters $d = D$ are equal, the value $c$ from Fig. 2 is equal to:

$$c = l \cdot \quad 1 - \frac{2 \cdot h}{l^2 + 4 \cdot D^2} \quad , \tag{3}$$

where $l$ – distance between the attachment points of the lower links on the agricultural implement;
$h$ – length of the lower link of the mounted mechanism;
$D$ – distance from the axis of suspension of an agricultural implement on a mounted mechanism to the centre of mass of WSV.

Besides, the convergence angle $\gamma$ of the lower links of the WSV mounted mechanism should be equal to:

$$\gamma = 2 \cdot arc\,tan \quad \frac{l}{2 \cdot D} \quad . \tag{4}$$

Analysis of dependencies (3) and (4) for the mounted mechanisms of categories 4N and 4 according to ISO 730:2009 showed that, increasing the distance $D$ from 0.6 m to 1.6 m, the value of $c$ increases quadratically from 0.1 m to 0.6 m. Besides, the convergence angle $\gamma$ of the lower links also decreases quadratically from 85 deg to 40 deg. For the WSV experimental prototype the convergence angle $\gamma$ of its lower links was 65 degrees.

## Results and discussion

As a result of the experimental studies, it was established that the internal structure of oscillations of the heading angle $\varphi$ of WSV and the rotation angle $\beta$ of the lower links of its mounted mechanism with an agricultural implement, mounted on it in the two considered options for its mounting (see Fig. 2), are practically the same. As the analysis shows, the normalized spectral densities of both processes are almost within the same frequency ranges 0…3 $s^{-1}$ (Fig. 4).

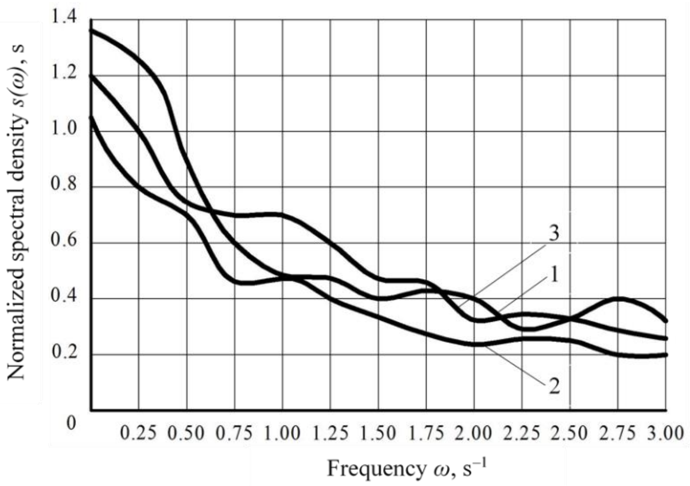


Fig. 4. **Normalized spectral densities of oscillations of the heading angle $\varphi$** (1) WSV of angle $\beta$ of rotation of the lower links of its mounted mechanism according to the first (2) and second option (3) (see Fig. 2) placement of an agricultural implement relative to the axis of its suspension

Oscillations of the heading angle $\varphi$ and angle $\beta$ of rotation of the lower links of its mounted mechanism were insignificant in terms of energy. But by the absolute value they are different. The dispersion of the parameter $\varphi$ was 2.24 deg$^2$, and the dispersion of the parameter $\beta$ for the first option of placing an agricultural implement on the mounted mechanism was 2.64 deg$^2$ , and 3.96 deg$^2$ for the second option. However, according to the well-known Fisher F-test, the null hypothesis of the equality of these statistical estimates at a significance level of 0.05 is not rejected. That is, it can be argued that the dispersion of oscillations in the angle of rotation of the linkages of the mounted mechanism is not by chance greater than the dispersion of oscillations in the heading angle of WSV. In principle, this result is logical since WSV, together with the agricultural implement rigidly attached to it, is able to withstand the disturbances that it generates during the soil cultivation.

When comparing the two considered schemes for placing an agricultural implement on a mounted WSV mechanism from the position of its more stable movement (less vibrations), the first scheme has an advantage (Fig. 2) since the dispersion of vibrations of the implement in this case is 33.3% less than in the second scheme.

Despite the fact that the WSV wheels move along the tracks of a constant tramline, the issue of the straightness of its movement is to a certain extent topical. First of all, the nature of the stability of the WSV movement is reflected in the straightness of the trajectory of the furrows when cultivating the soil with its working body.

The investigations, carried out, have established that in the first option of placing an agricultural implement on the WSV mounted mechanism (Fig. 2), we have satisfactory and better trajectory indicators from the furrow of the working body when cultivating the soil. The basis for this conclusion is the nature of the oscillations of the trajectory of the furrow of the treated soil, laid by the working body of the agricultural implement. These oscillations are of low-frequency (Fig. 5), the dispersion value is 3.6 m$^2$, and the spectrum itself is concentrated in the frequency range 0...0.50 m$^{-1}$. At the movement speed of 2 m·s$^{-1}$ this amounts to 0…1.0 s$^{-1}$ or only 0…0.16 Hz. The length of correlation between the oscillations of the furrow trajectory of the treated soil with the WSV working body is at least 10 m.

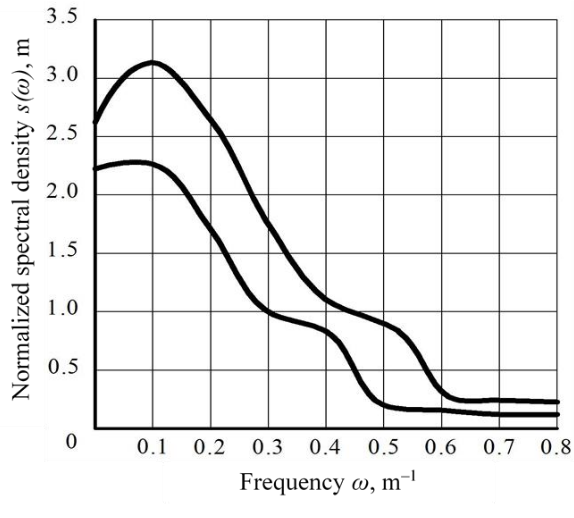


Fig. 5. **Normalized spectral density of oscillations of the trajectory of the furrow laid by the working body of an agricultural implement according to the first option** (1), and the second option (2) of its placement relative to the suspension axis (Fig. 2)

At the same time, according to the first option of placing the implement on the WSV mounted mechanism, the result, obtained in terms of the frequency of the process, is satisfactory since the cutoff frequency of the spectral density of oscillations of the furrow trajectory on the soil from the working body is $\omega$ = 0.50 m$^{-1}$, which is less, compared to the second option of its placement on a mounted mechanism, where the cutoff frequency is $\omega$ = 0.64 m$^{-1}$.

Since the WSV moves along the tracks of a constant tramline, then, on the one hand, the statistical characteristics of its heading angle (parameter $\varphi$) should not have significant differences from similar characteristics, in particular dispersion, as well as normalized correlation functions and spectral densities that represent oscillations of straightness of the tramline itself. But in fact, as the experimental studies show, this is not entirely true. Due to the presence of slip angles of the tires of the WSV wheels, the energy (i.e. dispersion) and the internal structure of the oscillations of its heading angle are somewhat greater than the dispersion of the oscillations of the straightness of the tramline itself. In numerical terms, the dispersion of the oscillations was 2.24 deg$^2$, and the dispersion of the tramline straightness was 1.96 deg$^2$. In addition, the null hypothesis about the equality of the estimated dispersions, using the Fisher F test, is not rejected. With a probability of 95% it can be stated that the dispersion of oscillations in the WSV heading angle is not by chance greater than the oscillations in the straightness of the constant tramline.

Despite the difference in the nature of oscillations in the heading angle $\varphi$ of WSV and angle $\beta$ of rotation of the lower links of its mounted mechanism in various options for placing an agricultural implement on it, there is a close correlation between them. This correlation is unambiguously represented by the normalized cross-correlation function (Fig. 6). Analysis of its course shows that there is a certain correlation between the input influence – the heading angle of WSV and the output parameter - the angle of rotation of the lower links of its mounted mechanism. The maximum value of the cross-correlation function is positive and quite high for the first option of placing the tool on the WSV mounted mechanism and reaches 0.82 (Fig. 6).

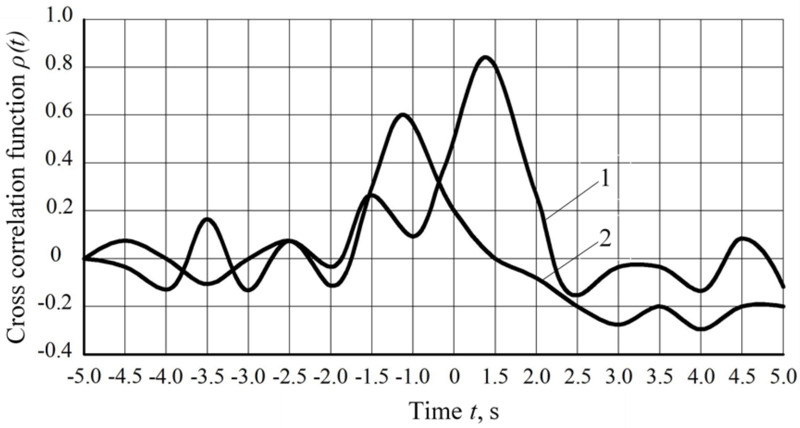


Fig. 6. **Cross-correlation function of oscillations of links of the mounted mechanism for the heading angle according to the first option** (1) of placing the working body on the mounted mechanism relative to the suspension axis and the second option (2)

A displacement of the maximum value of the cross-correlation function to the right of the vertical axis by 1.2 s (see Fig. 6) for the first option of placing an agricultural implement on the mounted mechanism indicates that the angle of rotation of the links of the mounted mechanism is a function of the heading angle of WSV, and not vice versa. It is in the same amount of time that the change in the angle of rotation of the lower links of the mounted WSV mechanism lags behind the disturbing impact – the heading angle of rotation of WSV.

In the case of the second option for placing the agricultural implement on the WSV mounted mechanism, the maximum was in the first quadrant (Fig. 6). In this case the oscillations in the angle $\beta$ should be considered as a disturbing effect of the mounted mechanism upon the linear movement of WSV, and, as a consequence, an undesired reaction, and its undesirable rotation as a result in one direction or another.

As a result of the research, it has been proved that the best option for placing an implement on the WSV mounted mechanism is to place it behind the attachment axis. Based on the analysis of the above cross-correlation function (Fig. 6), it can be assumed that such a solution does not lead to a deterioration in the straightness of the movement of the experimental WSV sample, in contrast to the option of placing the agricultural implement on the mounted mechanism in front of its attachment axis.

In further research it is purposeful to study the processes of the WSV dynamic system, working out by the dynamic system WSW the control and disturbing impacts (the angle of rotation of the lower links of the mounted mechanism) during its plane-parallel movement in a horizontal plane, using the amplitude and phase-and-frequency characteristics.

## Conclusions

1. It can be asserted with a probability of 95% that the dispersion of oscillations in the heading angle of WSV is not by chance greater than the oscillations in the straightness of the tramline along which the WSV is moving. Such a result is explained by the manifestation of the deviation (slip) angles of the WSV wheels in a horizontal plane.
2. From the position of a more stable movement of WSV (less oscillations), the scheme of placing an agricultural implement on the mounted mechanism behind the axis of its attachment has an advantage since the dispersion of oscillations of the implement in this case is by 33% less than in the option of placing it in front of the axis of its attachment. These oscillations are of low frequency and constitute a spectrum of 0…0.16 Hz. The length of the correlation link of oscillations of the furrow trajectory of the soil treated by the WSV working body is at least 10 m.
3. There is a close correlation between the oscillations of the heading angle of WSV and the rotation of the lower links of its mounted mechanism. The maximum significance of the cross-correlation function is quite high and reaches 0.82.
4. The shift of the maximum value of the correlation function to the right by 1.2 s indicates that the rotation of the mounted mechanism in the option of placing the working element on it behind the suspension axis is a function of the heading angle of WSV. In the case of placing the agricultural implement on a mounted WSV mechanism in front of the suspension axis, vibrations of the mounted mechanism should be considered as a disturbing effect on the linear movement of WSV, and, as a consequence, an undesirable reaction, and its undesirable rotation, as a result, in one direction or another.

## Author contributions

Conceptualization, V.B. and S.P.; methodology, V.B., A.R., V.N. and V.A.; software, V.Ku.; validation, A.A. and V.B.; formal analysis, V.B, A.R. and S.P.; investigation, V.B., V.A., V.Ky., V.N. and V.Ku.; data curation, A.A., V.B. an S.P.; writing – original draft preparation, V.B., A.R. and V.N.; writing – review and editing, A.A. and V.B.; visualization, V.Ku., V.Ky.; project administration, V.B.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

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