EXPERIMENTAL CHECKING OF MATHEMATICAL MODELS DESCRIBING THE FUNCTIONING ADEQUACY OF BRIDGE SYSTEMS IN AGRICULTURAL TRACK SYSTEM

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TILTU VEIDU UZBŪVES MATEMĀTISKĀ MODEĻA ATBILSTĪBAS EKSPERIMENTĀLA PĀRBAUDE PRAKTISKAI IZMANTOŠANAI LAUKSAIMNIECĪBAS TRANSPORTA SISTĒMĀ

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ABSTRACT

The article exposes the results of the mathematical simulation of the agricultural bridge equipment functioning. The mathematical models describing the functioning of the agricultural bridge equipment were checked for adequacy by comparing the theoretical and experimental amplitude-frequency characteristics of the oscillations of its heading angle and lateral displacement. It was established by the result of investigated characteristics' quantitative assessment that a satisfactory coincidence of the theoretical and experimental results, as well as a positive result of checking the adequacy of the mathematical models of the vertical and the horizontal oscillations of the agricultural equipment indicate a possibility of their further use for solving scientific and practical problems.

ABSTRACT

Rakstā aprakstīta metodika, kas paredzēta lauksaimniecības tiltu veida aprīkojuma funkcionēšanas matemātiskās modelēšanas rezultātu atbilstības pārbaudei, izmantojot dinamisko sistēmu automātiskās regulēšanas teoriju. Lauksaimniecības tiltu veida aprīkojuma darbību raksturojošo matemātisko modeļu atbilstība tika pārbaudīta, salīdzinot teorētiskos un eksperimentālos amplitūdas frekvences raksturlielumus tā virziena leņķa svārstībām un sānu pārvietojumam. Ar izpētīto kvantitatīvā novērtējuma rezultātiem tika noskaidrots, ka ir apmierinoša teorētisko un eksperimentālo rezultātu sakritība, kā arī pozitīvs rezultāts, pārbaudot lauksaimniecības tehnikas vertikālo un horizontālo svārstību matemātisko modeļu piemērotību, norāda uz iespēju tos turpmāk izmantot zinātnisku un praktisku problēmu risināšanai.

INTRODUCTION

Contemporary development of science and technology cannot be imagined without a wide use of the mathematical simulation methods. In recent years, mathematical simulation as a method of studying complex technical systems in agriculture has been widely used to solve various problems. They include investigations of the new agricultural bridge equipment in order to ensure its operation by the principle of gauge and bridge farming (*Chamen et al., 1994; Bochtis et al., 2010; Onal, 2012; Bulgakov et al., 2017a*). According to many scientists, such agricultural bridge equipment is a prospect for the transition from the traditional tractor-harvester technologies to more modern farming. And their functioning allows solving the main contradiction in the "mover-soil" system the essence of which is that, in order to achieve high traction and adhesion properties by the energy tool, its movers must be in contact with a dry and dense base while normal growth of the cultivated plants needs an optimally moist and fluffy soil environment (*Nadykto, 2017; Adamchuk et al., 2016*). This is possible only if the plant growth zone (the agrotechnical zone of the field) and the track of the movers of energy tools (the technological or engineering zone) are clearly separated in the field. In such a case the movement of the energy tools becomes strictly regulated (routed), and it is provided for exclusively pre-formed tracks – constant tramlines.

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At the first stage of the theoretical research of the agricultural bridge tools, the mathematical simulation of their functioning, using the software and algorithmic tools and the PC, provides valuable scientific information about the dynamics of their plane-parallel movement, and much more. In this case one main circumstance should be considered that taking advantage of the methodology of mathematical simulation to study the functioning of such new technical systems is possible only if the physical reality is adequately reflected in the mathematical and computer models.

Provided that modern software environments are used (for example, Mathematica, Statistica, Mathcad, MS Excel, and the like), checking the regression mathematical models for adequacy is a formalised procedure (*Nadykto, 2017*).

However, this formalised methodological approach for checking mathematical models in terms of adequacy is not always acceptable and possible to be implemented. So, for example, when simulating the behaviour of complex dynamic systems, such as agricultural bridge tools, the most informative is the use of statistical dynamics methods and the theory of automatic regulation of linear dynamic systems when they reproduce statistically random control and disturbing input actions. According to this methodology, based on the constructed differential equations, transfer functions are compiled, and then the amplitude-frequency characteristics are calculated (*Chamen, 2015; Bulgakov et al., 2016a; Bulgakov et al., 2018*). At the same time, assessment of the adequacy of the theoretical amplitude-frequency characteristics of the development of the input disturbance by the dynamic system to be studied is a rather complicated task. Its complexity is determined by the impossibility to apply a formalised programmatic checking procedure for adequacy.

In scientific publications (*Bulgakov et al., 2016b; Bulgakov et al., 2017b*), a methodology for checking the adequacy of mathematical models is described, the solution of which is represented by the amplitude-frequency characteristics of the development of external disturbances acting upon it by a machine-tractor aggregate. But the algorithm itself of the hardware search and formalisation of the input and output parameters is not sufficiently presented in the indicated scientific works.

The purpose of the research is to test the methodology for checking the results adequacy of the mathematical simulation of the agricultural bridge equipment functioning, using the provisions of the theory of dynamic systems' automatic regulation to improve the quality of this procedure.

MATERIALS AND METHODS

There were tested for adequacy a mathematical model of the agricultural bridge tools functioning in a vertical and a horizontal plane, obtained by us as a result of theoretical investigations and described in detail in the scientific papers (*Bulgakov et al., 2017c; Bulgakov et al., 2019*).

We will test the mathematical model of horizontal oscillations of the agricultural bridge equipment for adequacy by comparing the theoretical $A_T(\omega)$ and experimental $A_E(\omega)$ amplitude-frequency characteristics of oscillations of its heading angle φ and lateral displacement x_s (as the output values) when it (the agricultural means) works out the input control action. As the last one, the driving force of the wheels of one of the sides $P_{\partial л}$ of the agricultural tool was used with the onboard power method of turning it.

The mathematical model of vertical oscillations of the agricultural bridge equipment was checked for adequacy by comparing the theoretical $S_{Ta}(\omega)$ and the experimental $S_{Ea}(\omega)$ normalised spectral densities of its vertical oscillations. For the input parameter we took the oscillations in the irregularities of the longitudinal profile of traces of a constant tramline along which the agricultural tool is moving, and for the output parameter – the oscillations of its frame. The theoretical amplitude-frequency characteristics of the oscillations of the heading angle φ and the lateral displacement x_s of the agricultural bridge equipment, when it worked out the control action with the power control method, as well as when it worked out the oscillations of the irregularities of the path profile, were calculated using the corresponding transfer functions (*Bulgakov et al., 2017; Bulgakov et al., 2019, Pascuzzi et al., 2020, Ivanovs et al., 2020)*. To determine the experimental amplitude-frequency characteristic under the laboratory and field conditions, we studied the agricultural bridge equipment in an aggregate with the tooth harrows (type BZSS-1.0) (Fig. 1), which are structurally made like harrow (*Nadykto, 2013*).

To conduct research under the laboratory conditions, a constant tramline was artificially created on the soil, the longitudinal profile of the irregularities of which was finally formed by multiple passes of the wheels of the agricultural tool along it. The control of the agricultural bridge equipment was carried out by the operator in a manual mode. The principle of its control was, when the agricultural bridge equipment deviates from rectilinear movement along the tracks of a constant tramline, the operator monitors the movement of a special device. In this role was the centre of the wheel of one of the sides of the agricultural tool at the level of the supporting surface passing through the central line of the tire track. The task of the control of the agricultural tool was to ensure that the centre of its wheel at the level of the supporting surface is as close as possible to the axis of symmetry of the constant tramline.

Fig. 1 - Agricultural bridge equipment as part of a harrowing aggregate, during the research

The operator corrected deviation of the trajectory of the sighting point by reducing (almost to zero) the tangential traction force $P_{\partial л}$ on the wheels of the agricultural tool from one of its sides. In particular, if there was a right-hand deviation of the agricultural tool from the direction of its movement, then the tangential traction force decreased on the left side wheels, and vice versa. As a result of this operator’s action the agricultural tool changed its heading angle accordingly. Acceptable controllability of the movement of the agricultural bridge equipment was achieved when the duration of the control action was sufficient so that it was able to compensate for the amplitude of its heading angle or lateral displacement without leaving the wheels beyond the established constant tramline width.

In the process of experimental tests of the agricultural bridge equipment by means of an analogue-to-digital converter, a PC and a mobile communicator, there were simultaneously recorded:

– the heading angle φ (deg.);

– the vertical accelerations Z (m·s^{-2}) of the frame of the agricultural tool;

– duration $\tau_{P\partial л}$ (s) of the control action to restore its rectilinear movement as a result of deviation from it.

The first two parameters during experimental investigations were recorded using a mobile communicator with the Android operating system. In this software environment, using a special Accelerometer Meter application (version 1.32), there were recorded in time the digitised output signals and their frequency spectrum from the accelerometer sensors, built into the mobile communicator (Fig. 2).

a) b)

Fig. 2 - A mobile communicator (a) and Android-based Accelerometer Meter interface (b) for measuring vertical acceleration Z and heading angle φ of the agricultural bridge equipment

Also, in the process of experimental investigations of the agricultural bridge equipment there was measured the amplitude x_s of its lateral deviation from the axis of symmetry of the constant tramline. For this purpose, the shortest distance from the axis of symmetry of the constant tramline to the midpoints of the trajectories of its front and rear wheels from one side with a step of 0.2 m was measured (Fig. 3).

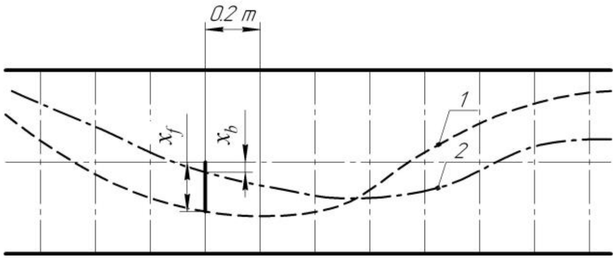

Fig. 3 - A scheme for the determination of the agricultural tool lateral displacement:
1, 2 – respectively, the middle points of the trajectories of its frontal and rear wheels within the tramline

Since the amplitude of the heading angle φ of the agricultural bridge equipment did not exceed 6...8 degrees, the amplitude x_s of the transverse displacement of its mass centre was calculated with sufficient accuracy according to Fig. 3 by expression:

$$x_s = \frac{x_f - x_b}{2}, \tag{1}$$

where x_f , x_b – the distances (m) from the axis of symmetry of the constant tramline to the middle of the trajectories of the frontal and rear wheels of the agricultural equipment, respectively.

The characteristics of irregularities' oscillations of the longitudinal profile of constant tramline traces were recorded using an automated profilograph with an analogue-to-digital converter and a PC (Fig. 4) according to the method, described in detail in (*Bulgakov et al., 2019*).

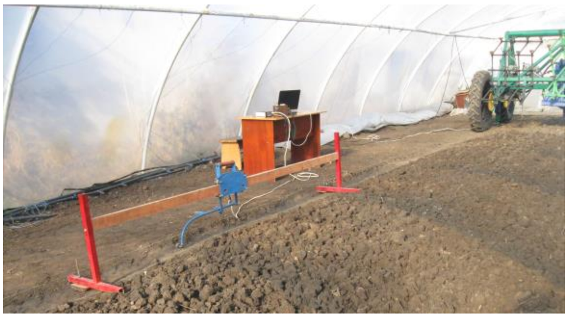

Fig. 4 - A hardware-measuring complex for profiling the irregularities of a constant tramline traces

From the obtained arrays of realisations of the input and output parameters, such statistical characteristics as standard deviations and normalised spectral densities were determined using the technique, presented in (*Nadykto, 2017; Gmurman, 2016*).

The experimental amplitude-frequency characteristic of the functioning of the agricultural bridge equipment was calculated according to expression (*Nadykto, 2017*):

$$A(\omega) = \frac{\sigma_y}{\sigma_x} \cdot \left(\frac{S_y(\omega)}{S_x(\omega)} \right)^{\frac{1}{2}} \tag{2}$$

where:

σ_x, $S_x(\omega)$ – the mean-square deviation and normalised spectral density of the input quantity;

σ_y, $S_y(\omega)$ – the mean-square deviation and normalised spectral density of the output quantity;

ω – the frequency of oscillations of the control impact, s^{-1}.

The theoretical spectral density of the output parameter oscillations was found according to expression (*Nadykto, V., 2017*):

$$S_T(\omega) = \frac{A_T(\omega)^2 \cdot S_x(\omega) \cdot D_x}{D_y} \tag{3}$$

where:

$S_x(\omega)$, D_x – the normalised spectral density and dispersion of oscillations of the input value;

D_y – dispersion of oscillations of the input value.

Dispersions of the characteristics of random processes at the output of a linear dynamic system were found according to expression:

$$D_y = \int_{\omega_{st}}^{\omega_{zr}} S_y(\omega) d\omega \qquad (4)$$

where:

ω_{st}, ω_{zr} – the initial value of the frequency range of the spectral characteristics and the cut-off frequency.

Since the ordinate of the spectral density of oscillations of the agricultural tool frame vertical accelerations has a unit of measurement m·s^{-2}, which is the implementation of the signals from the accelerometer sensors, in order to pass to the linear amplitude z_y (m), the ordinate of the points of the indicated spectral density, were recounted with some assumption and with sufficient accuracy as follows:

$$z_y = \frac{Z \cdot T^2}{2} \qquad (5)$$

where:

Z – acceleration of vertical oscillations according to the data of the Accelerometer Meter software environment, m·s^{-2};

T – the time, equal to the length of the correlation of the density of accelerations of the agricultural tool vertical oscillations, s.

A quantitative statistical assessment of the compared theoretical and experimental data adequacy was done by testing the null hypothesis on the equality of the compared dispersions of the initial value fluctuations according to the Fisher F-test. If the calculated value of the Fisher F-test was less than the critical value, then the zero hypothesis on the equality of the compared variances was not rejected (at a certain statistical significance level). Besides, the number of the degrees of freedom was taken equal to 10, since the graphs of the spectral density of fluctuations of the considered input and output parameters were calculated from such a number of points. In such a case the critical value of the Fisher F-criterion at a statistical significance level of 0.05 was 2.97, and at a level of 0.01, it was 4.84, respectively.

RESULTS AND DISCUSSION

As the analysis of the obtained and processed experimental data showed, the fluctuation spectrum of the control impact of the agricultural bridge equipment with the onboard power method of its control is of low-frequency nature (Fig. 5). The main dispersion spectrum of this parameter is concentrated in the frequency range 0...2 s^{-1}, which corresponds to 0...0.32 Hz. Almost in the same frequency range, the dispersion of fluctuations of the output parameter, that is, the heading angle φ of the agricultural tool is also concentrated (Fig. 5). The standard of fluctuations of this parameter was ± 0.014 rad.

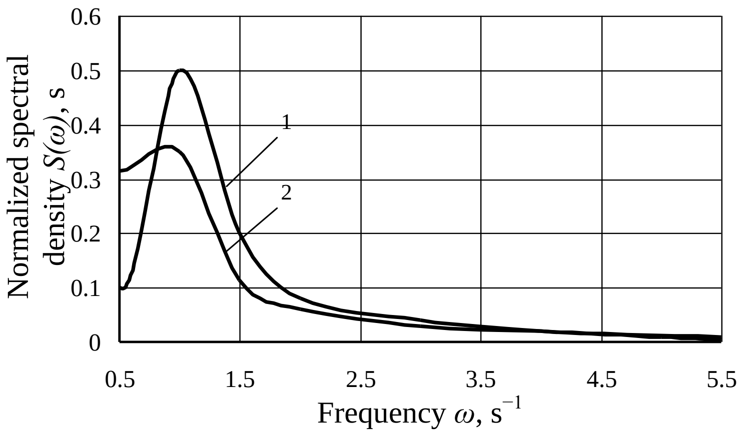

Fig. 5 - Normalised spectral densities of fluctuations of the tangential traction force (1) of the agricultural tool and its heading angle (2)

Further calculation of the experimental amplitude-frequency characteristic of the agricultural bridge equipment and its comparison with the theoretical characteristic (Fig. 6) showed that in the operating frequency range 0...2 s^{-1}, the difference between the fluctuations of the input and the output signals does not exceed 15%.

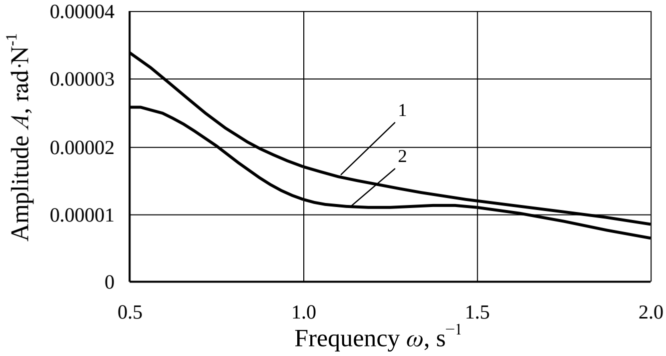

Fig. 6 - Theoretical (1) and experimental (2) amplitude-frequency characteristics of the fluctuations in the heading angle *φ*

The result of a quantitative assessment of the characteristics in Fig. 6 showed that, according to the Fisher F-test, the null hypothesis about the equality of the compared dispersions (1.57 s^2 and 1.67 s^2) does not deviate neither at the static significance level of 0.05 nor at the level of 0.01.

Fluctuations of the lateral displacement of the agricultural bridge equipment as part of a harrowing aggregate are also of a low-frequency nature (Fig. 7). The main spectrum of dispersions is concentrated in the frequency range 0...2 s^{-1}. The standard of fluctuations of this parameter is ± 0.05 m.

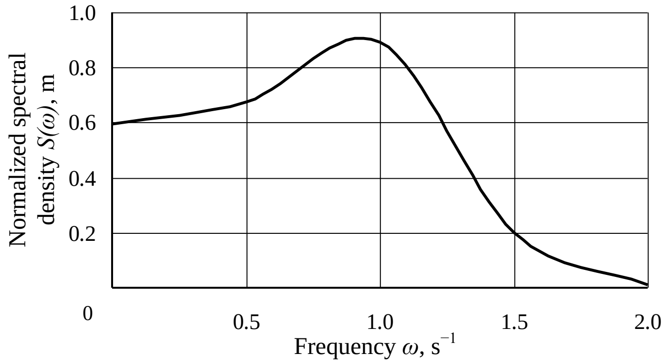

Fig. 7 - Normalised spectral densities of fluctuations of the linear transverse displacement x_s of the agricultural bridge equipment

Calculation of the experimental amplitude-frequency characteristic according to (2) and its comparison with the theoretical one showed (Fig. 8) that in the operating frequency range of 0...2 s^{-1} oscillations of the input signal, the greatest difference between the theoretical and the experimental data does not exceed 15%.

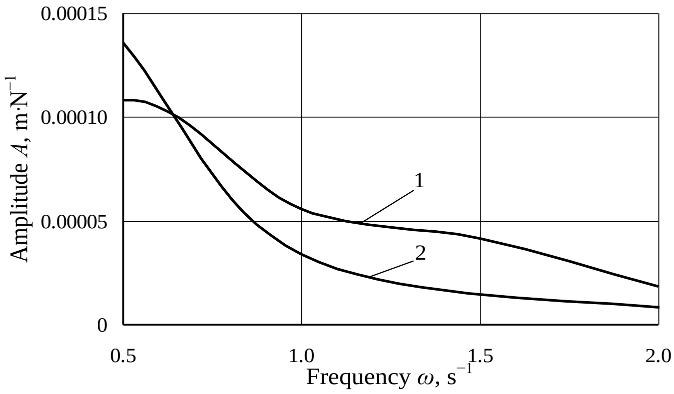

Fig. 8 - Theoretical (1) and experimental (2) amplitude-frequency characteristics of the fluctuations of the linear transverse displacement x_s of the agricultural equipment as part of the harrowing aggregate when working out the control impact

As a result of measuring the characteristics of the irregularities of the constant tramline tracks' longitudinal profile, a graph of the normalised spectral density of the amplitudes of their fluctuations was obtained (Fig. 9).

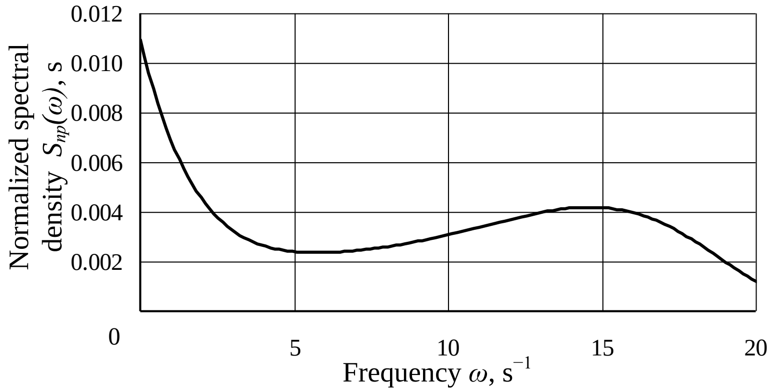

Fig. 9 - The normalised spectral density of irregularities of the constant tramline traces' longitudinal profile, according to the hourly argument

From the analysis of Fig. 9 it follows that the working frequency range of fluctuations in the irregularities of the constant tramline traces' profile is 0...20 s^{-1} (or 0...3.2 Hz). In this frequency range a mathematical model of the dynamics of vertical fluctuations of the agricultural bridge equipment in a vertical plane was checked.

A comparison of the theoretical $S_{Ta}(\omega)$ and the experimental $S_{Ea}(\omega)$ normalised spectral densities of vertical oscillations of the frame of the agricultural bridge tool shows (Fig. 10) that both processes are characterised by approximately the same nature of the change in the frequency range.

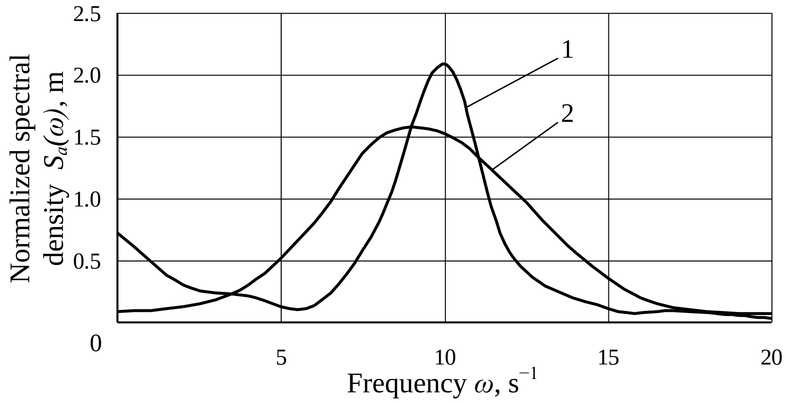

Fig. 10 - Theoretical (2) and experimental (2) normalised spectral densities of vertical oscillations of the frame of the agricultural bridge tool

The difference in the maximum theoretical dispersion (see Fig. 10) attributed to ω_T = 10 s^{-1} and the experimental one ω_T = 9 s^{-1} is 1 s^{-1}. As testing of the null hypothesis about the equality of the theoretical dispersion D_{Ta} = 1.21 sm^2 and the experimental dispersion D_{Ta} = 1.56 sm^2 according to the Fisher F-test showed, it does not deviate at the static significance levels of 0.05 and 0.01.

The satisfactory agreement of the above theoretical and experimental results, as well as the positive result of checking the mathematical models of the agricultural bridge equipment for adequacy, indicates the possibility of their further use for solving scientific and practical problems.

CONCLUSIONS

Thus, the adequacy of the conducted investigations confirms the fact that mathematical simulation of functioning of the agricultural bridge tools, using the theory of automatic regulation of dynamic systems, is quite effectively verifiable. At the same time, for experimental registration of such parameters of the agricultural bridge tool as the characteristics of its heading angle and vertical movements, a mobile Android-based communicator with accelerometer sensors and the Accelerometer Meter application integrated in it is sufficient.

A positive result of checking for adequacy the functioning of the mathematical models of the TSATU agricultural bridge equipment that we developed earlier indicates the possibility of their further use for solving scientific and practical problems.

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