DEVELOPMENT OF ADVANCED METHODOLOGY OF EXPERIMENTAL RESEARCH ON OSCILLATION PROCESSES INTENSITY FOR MACHINE-TRACTOR UNITS
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РОЗРОБКА НОВОЇ МЕТОДИКИ ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ ІНТЕНСИВНОСТІ КОЛИВАЛЬНИХ ПРОЦЕСІВ МАШИННО-ТРАКТОРНИХ АГРЕГАТІВ

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ABSTRACT
An important operational indicator of agricultural machine-tractor units is the smoothness of movement, which significantly affects the traction and dynamic performance of their work, productivity, agronomic qualities of the operation, traffic safety, durability and efficiency. This article presents an improved method and results of experimental assessment of the smoothness of the modular agricultural unit movement, which moves in the footsteps of a constant technological track. Studies of the modular agricultural unit smoothness showed that the graphs of normalized correlation functions of vertical oscillations of the modular agricultural tool developed by us in its motion in the wake of a constant technological track is characterized by a function containing, along with random components, harmonics, which are expressed by attenuating periodic oscillations. The range of oscillations frequencies of the modular agricultural unit frame is concentrated in the range from 0 to 20 s^{-1}, which is consistent with the frequency range 0…0.3 s^{-1} in which the dispersion of fluctuations of profile irregularities is concentrated in traces of the technological track. The developed technique of mathematical modelling and experimental determination of vertical oscillations of the machine-tractor unit can be used to study the dynamics of other agricultural machines and units.

АНОТАЦІЯ
Важливим експлуатаційним показником сільськогосподарських машинно-тракторних агрегатів є плавність ходу, яка суттєво впливає на тягово-динамічні показники їх роботи, продуктивність, агротехнічні якості експлуатації, безпеку руху, довговічність і економічність. У статті наведено нову методику та результати експериментальної оцінки плавності руху модульного сільськогосподарського агрегату, який рухається по слідах постійної технологічної колії. Дослідження плавності модульного агрегату показали, що розроблений нами графік нормованих кореляційних функцій вертикальних коливань модульного сільськогосподарського знаряддя при його русі по слідах постійної технологічної колії характеризується функцією, що містить поряд із випадковими складовими гармонічні, які виражаються загасаючими періодичними коливаннями. Діапазон частот коливань рами сільськогосподарського знаряддя зосереджено в діапазоні від 0 до 20 c^{-1}, що узгоджується з діапазоном частот 0…0.3 c^{-1}, в якому дисперсії коливань нерівностей профілю зосереджено слідів технологічної колії. Розроблена методика математичного моделювання та експериментального визначення вертикальних коливань машинно-тракторного агрегату може бути використана при дослідженні динаміки інших сільськогосподарських машин та агрегатів.

INTRODUCTION

The quality of many technological processes in agriculture is connected with uniform (smooth) movement of the working bodies for their implementation *(Lou et al., 2021; Shahgoli et al., 2010; Woźniak et al., 2019; Enlai et al., 2019)*. Agricultural machine-tractor units in the process of their working movement are transmitted inclinations, shocks and impacts caused by unevenness of the longitudinal profile of the track, uneven traction resistance and other factors *(Kuvachov et al., 2021)*. In general, the energy and technological parts of agricultural machine-tractor units carry out the oscillations that determine their smooth motion. Smoothness of agricultural units movement is one of the important operational indicators of their work, which is assessed by the impact of oscillations (translational vertical, transverse, angular longitudinal, etc.), mainly on the physical condition and health of the operators who operate them *(Bulgakov et al., 2022; Hac et al., 2009; Szakács et al., 2010; Jazar, 2008)*. At the same time, there are other important indicators of machine-tractor units, which depend on the smoothness of movement: traction and dynamic performance, productivity, agronomic qualities of the operation, traffic safety, durability and efficiency *(Bulgakov et al., 2022)*.

It is known from the theory on the tractor and the car *(Bulgakov et al., 2022)* that the main influence on the movement smoothness and driver's physiological state is exerted by two types of oscillations: translational vertical (jumping) and angular longitudinal (galloping). In turn, the movement smoothness depends on the microrelief of the surface, the skill of the driver, the layout of the unit, the type of running gear, speed, imbalance of parts, uneven rotation.

The research on the dynamics of agricultural tractor-implement units has been the subject of quite a number of studies *(Bulgakov et al., 2016; Xu et al., 2015; Rabbani et al., 2011; Mitsuoka et al., 2008; Mircea et al., 2014; Karkee, 2009)*.

These techniques consider a bunch of heterogeneous indicators for assessing the movement smoothness of mobile vehicles:

– the largest vertical displacement of the centre of elasticity and angular oscillation of the frame;

– largest and average angular or linear accelerations;

– the largest elementary changes in angular or linear accelerations attributed to the corresponding elementary time intervals;

– an indicator of the intensity of shocks on the driver's body, in Piles;

– vibration load and more.

From the position of high versatility, any machine-tractor unit should be aggregated with almost all trailed, semi-mounted and mounted agricultural machines and implements. In addition, the technological part of the unit, regardless of the method of its aggregation, can cause a redistribution of the coupling weight on the front and rear wheels of the tractor, and, with vertical tillage, the weight of the tractor is used to create a cutting force, as a result of which the reaction of the movers to the ground is reduced. At the same time, according to the results of our experimental studies, the unevenness of the longitudinal profile in the traces of a constant technological track has a different frequency spectrum than the usual agricultural background *(Kuvachov et al., 2021; Mitkov, et al., 2021; Bulgakov et al., 2021)*. Therefore, the vertical oscillations of a dynamic system are caused by different characteristics of the perturbations. The latter, on the one hand, are caused by irregularities in the traces of a constant technological track when the tractor propellers move along it, and on the other hand, from the irregularities of the agricultural background, along which the supporting wheels of agricultural machines move.

The dynamics of the movement of the machine-tractor units in the vertical plane is determined by the incoming disturbing influences. The latter include irregularities in the longitudinal profile of traces of a constant technological track and uneven traction resistance of agricultural machines and implements. It is clear that the nature of the internal structure of the tramline longitudinal profile certainly affects tractor smoothness and fluctuations in its tractive effort with all the negative consequences *(Deynichenko et al., 2018; Bulgakov et al., 2021)*.

It is known that the quality of processing by any dynamic system of the input variables depends on its characteristics. Regarding the machine-tractor unit, these are its scheme, as well as design and other parameters. Therefore, the correct choice of the latter from the standpoint of the desired movement smoothness provides it with optimal transformation of the disturbing impacts affecting it.

To conduct scientific research of a machine-tractor unit movement in a longitudinal-vertical plane, one should use the methods of statistical dynamics, described in detail by A.B. Lurie, as used in (*Bulgakov et al., 2016; Bulgakov et all., 2021)*.

According to these methods it is known that the transforming properties of a dynamic system may be expressed by the transfer functions and frequency characteristics *(Kuvachov et al., 2021; Mitkov, et al., 2021; Bulgakov et al., 2021)*.

It is these characteristics, according to many scientists, that give the most complete and physical idea of the agricultural unit reactions to various disturbances, as well as the transient and stable processes of its operation.

The theoretical analysis of the transfer functions and frequency characteristics requires a system of corresponding differential equations, relating the input variables, to input disturbances, that is, a mathematical model of the process itself. At this stage of research, it is purposeful to consider it by means of a system of linear equations. Such idealization is quite efficient in this case since the dynamics of the movement of complex multielement aggregates has not yet been studied enough. And the knowledge gained about it makes it possible to physically comprehend the result obtained, and accumulate experience of designing.

The general method for solving the dynamics problems of a mechanical system in this case are vertical oscillations of the tractor frame and its technological part, which is a system of fairly complex differential equations, built on the basis of the Lagrange equations of the second kind *(Kuvachov et al., 2021; Mitkov, et al., 2021; Bulgakov et al., 2021)*. To construct an equivalent scheme of a tractor with an agricultural implement, hung on it, it is expedient and sufficient to consider the vibrations of a flat figure that has the shape of its lateral projection in one vertical plane, coinciding with the longitudinal area of symmetry of its frame and the agricultural implement.

When studying the uniformity of an agricultural unit movement in longitudinal-vertical plane when it moves along field surface unevenness, it becomes necessary to assess this movement smoothness, for which it is necessary and sufficient to determine some specific indicators of "smoothness" from among generally accepted units of physical measurements: amplitude, frequency, speed and oscillations acceleration. The development and improvement of methods for determining these indicators is an important task in the field of research into dynamics of agricultural units movement.

The purpose of the article is to study the smoothness of the modular agricultural unit movement, which moves in the footsteps of a constant technological track by using a new method of estimating the intensity of vertical oscillations system based on a tablet computer with Android operating system with built-in accelerometer sensors and Accelerometer Meter application.

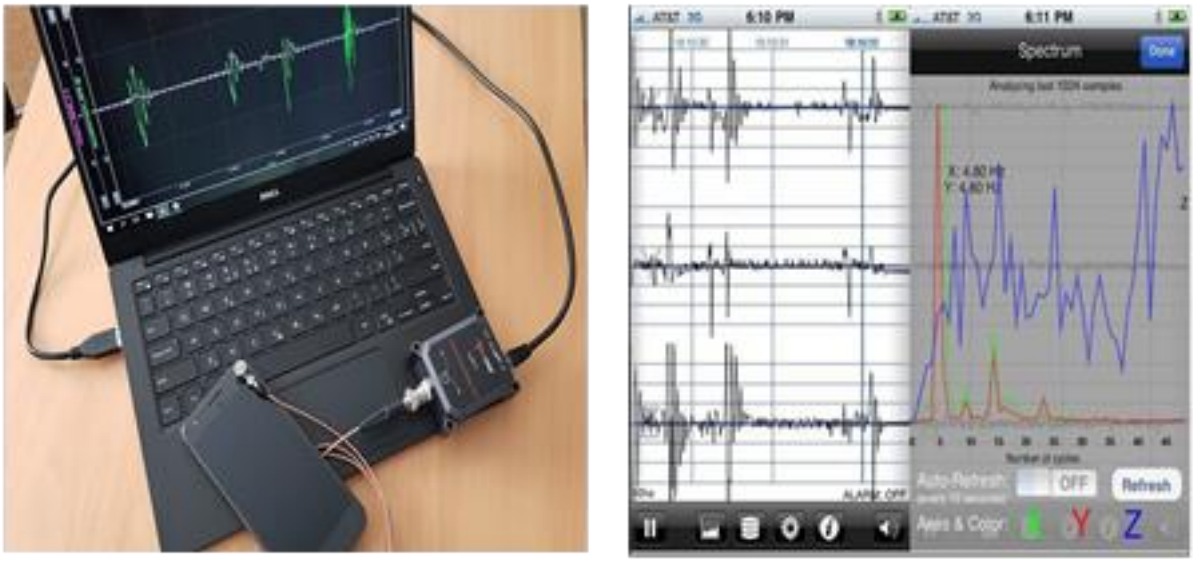
MATERIALS AND METHODS

For experimental studies, an arable modular machine-tractor aggregate was used, which consisted of an energy module (tractor), a technological module to it, and an attached plough (Figure 1). The design and properties of a modular machine-tractor aggregate are described in *(Bulgakov et al., 2021)*. The movement of the modular agricultural unit took place along the dirt traces of the constant technological track.

Fig. 1 – Modular agricultural unit as part of a mounted plough

To record the vertical accelerations of the agricultural machine frame in the process of its movement during the experimental studies, a tablet computer with the Android operating system was used (Figure 2). In this software environment, a special application Accelerometer Meter (version 1.32) received digitized output signals and their frequency spectrum from the accelerometer sensors (Figure 2).

The obtained digital signals from the accelerometer sensors of the tablet computer (see Figure 2) were imported into the Mathcad software environment to determine their statistical characteristics *(Zhiltsov, 2015; Borysova, 2021; Mazhayskiy et al., 2021; Hassan et al., 2022; Khadim et al., 2023)*.



a) b)

Fig. 2 – Accelerometer Meter software environment interface based on Android

a) the measuring system as part of the PC; b) measurement of vertical acceleration (marked Z).

Experimental ordinate of the spectral density of the vertical frame accelerations oscillations of the modular agricultural unit has a unit of measurement m·s^{-2}, which is the implementation of signals from the accelerometer sensors, then at the transition to a linear amplitude z_y (m) the ordinates of the points of spectral density, were determined as follows *(Zhiltsov, 2015)*:

$$z_y = \frac{\ddot{Z} \cdot T^2}{2} \text{ [m]} \quad (1)$$

where:

$\ddot{Z}$ – acceleration of vertical oscillations, m·s^{-2};

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

The theoretical spectral density of frame oscillations of modular agricultural unit was found from the next expression *(Kuvachov et al., 2021)*:

$$S_T(\omega) = \frac{[A_t(\omega)]^2 \cdot S_{pr}(\omega) \cdot D_{pr}}{D_e} \text{ [m]} \quad (2)$$

where: $S_{pr}(\omega), D_{pr}$ – normalized spectral density (m) and variance (m^2) path profile fluctuations;

$A_t(\omega)$ – theoretical amplitude-frequency characteristic which is transmitted to the frame of the unit from the field profile *(Bulgakov et al., 2021)*;

D_e – oscillation dispersion of machine-tractor aggregate.

The accuracy of measurements of the vertical displacements amplitude of a modular agricultural unit frame was evaluated by the value of the root-mean-square error *(Deynichenko et all., 2018)*:

$$\sigma_z = \sqrt{\left(\frac{T^2}{2}\right)^2 \cdot \sigma_{\ddot{Z}}^2 + \left(\ddot{Z} \cdot T\right)^2 \cdot \sigma_t^2} \text{ [m·s}^{-2}\text{]} \quad (3)$$

where:

$\sigma_{\ddot{Z}}$ and σ_t– standards for deviations of measurement errors of vertical frame acceleration of an agricultural machine and time.

The results of the studies showed that the reliability of the results obtained is such that the number of cases in which deviations from the patterns established in the course of experimental studies could occur did not exceed 10%.

RESULTS AND DISCUSSION

For mathematical modelling of the dynamics of the plane-parallel motion of a tractor as part of a machine-tractor unit, it is represented as an equivalent dynamic model (Fig. 3).

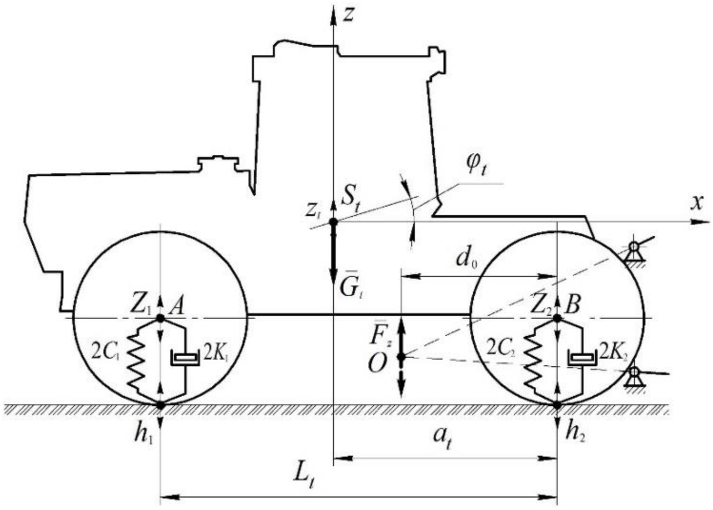


Fig. 3 – Scheme of fluctuations of the tractor in a longitudinal-vertical plane

Z_1, Z_2 – vertical movements of the front and rear axles of the tractor, respectively; h_1, h_2 – the height of the supporting surface unevenness under the front and rear wheels of the tractor; L_t, a_t – basis and the longitudinal coordinate of the tractor centre of gravity; M_t, J_t – mass and the moment of inertia of the tractor in a longitudinal-vertical plane; C_1, C_2 – the coefficients of elastic elements for the tractor front and rear axles, respectively; K_1, K_2 – the resistance coefficients of the dissipative elements of the tractor front and rear axles, respectively.

The mutual influence of the tractor and its technological part, according to the generally accepted principle of replacing rejected bonds by reactions, is expressed through the force F_z, which is concentrated in the instantaneous centre of rotation of the tractor rear mounted mechanism (point *O*, Fig. 3).

The calculated dynamic model of the plane-parallel movement of the tractor in a vertical plane has two degrees of freedom: vertical displacement (Z_t) of its centre of mass (point S_t) and angular fluctuations of the frame φ_t (Fig. 3).

Using the Lagrange equation of the second kind, the mathematical model of the tractor vertical fluctuations has the form:

$$\left.\begin{aligned} A_{11}\cdot\ddot{Z}_1 + A_{12}\cdot\dot{Z}_1 + A_{13}\cdot Z_1 + A_{14}\cdot\ddot{Z}_2 = f_{11}\cdot\dot{h}_1 + f_{12}\cdot h_1 + f_{13} \\ A_{21}\cdot\ddot{Z}_2 + A_{22}\cdot\dot{Z}_2 + A_{23}\cdot Z_2 + A_{24}\cdot\ddot{Z}_1 = f_{21}\cdot\dot{h}_2 + f_{22}\cdot h_2 + f_{23} \end{aligned}\right\} \quad (4)$$

where:

$$A_{11} = \frac{M_t\cdot a_t^2 + J_t}{L_t^2}$$
$$A_{12} = 2\cdot K_1$$
$$A_{13} = 2\cdot C_1$$

$$f_{11} = 2\cdot K_1$$
$$f_{12} = 2\cdot C_1$$
$$f_{13} = \frac{F_z\cdot d_0}{L_t}$$
$$A_{21} = \frac{[M_t\cdot(L_t - a_t)^2 + J_t]}{L_t^2}$$
$$A_{22} = 2\cdot K_2$$
$$A_{23} = 2\cdot C_2$$

$$f_{21} = 2\cdot K_2$$
$$f_{22} = 2\cdot C_2$$
$$f_{23} = F_z\cdot\left(\frac{1 - d_0}{L_t}\right)$$

Z_1, Z_2 – vertical movements of the tractor front and rear axles, respectively;

h_1, h_2 – the unevenness height of the supporting surface under the front and rear wheels of the tractor;

L_t, a_t – basis and the longitudinal coordinate of the tractor centre of gravity;

M_t, J_t – mass and the moment of inertia of the tractor in a longitudinal-vertical plane;

C_1, C_2 – the coefficients of elastic elements for the tractor front and rear axles, respectively;

K_1, K_2 – the resistance coefficients of the dissipative elements of the tractor front and rear axles, respectively.

As a result of experimental research it is established that the graphs of normalized correlation functions of vertical oscillations of the modular agricultural unit during its movement on the traces of a constant technological track are characterized by a function containing, along with random components, harmonics, which are expressed by attenuating periodic oscillations (Fig. 4).

The irregularities fluctuations of the traces profile of the constant technological track have the same character. The length of the correlation relation is about 0.16 s, which is equal to 0.35 m when the speed of the modular agricultural unit is within 2.2 m·s^{-1}. The obtained result is explained by the fact that the main spectrum of oscillations of the profile irregularities has a periodicity corresponding to the pitch of the ground hooks of the wheels tires of the modular agricultural unit *(Hac et al., 2009; Szakács, 2010; Jazar, 2008)*.

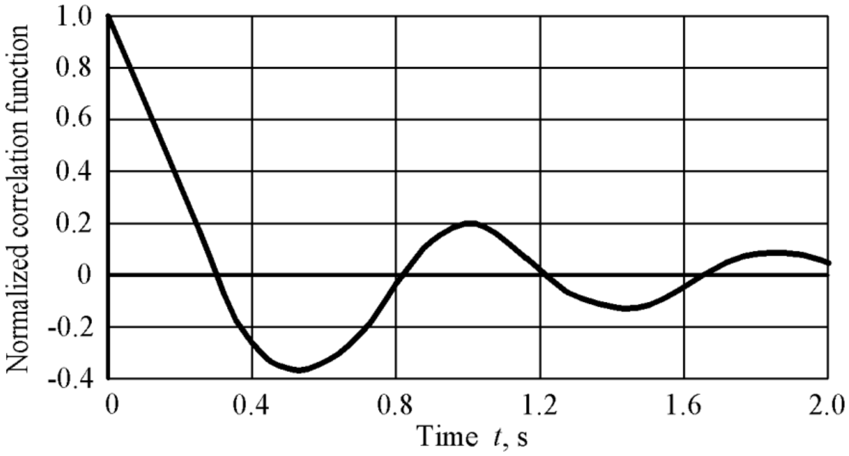


Fig. 4 – Normalized correlation function of accelerations of frame vertical oscillations of modular agricultural unit during its movement on a constant technological track

The experimental normalized spectral density of frame oscillations of modular agricultural unit during its movement on a constant technological track of field, which was measured using a developed methodology, is presented in Fig. 5.

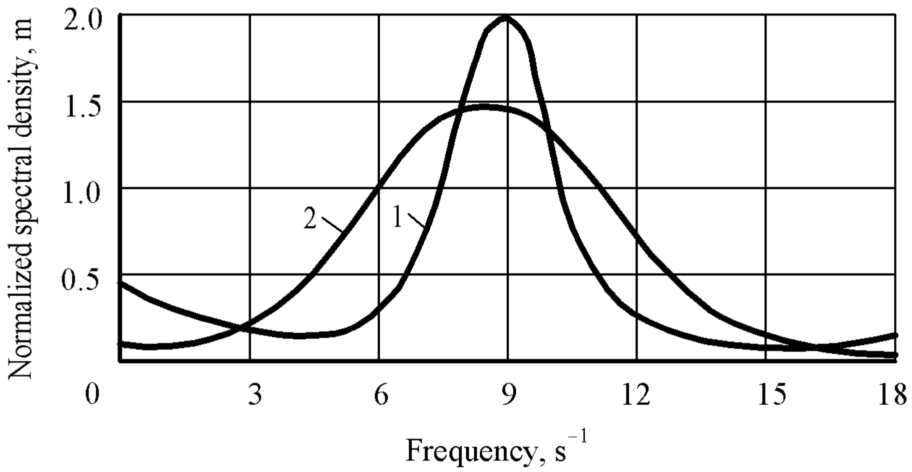


Fig. 5 – Theoretical (1) and experimental (2) normalized spectral densities of frame vertical vibrations of investigated machine and tractor unit

Fig. 5 shows the theoretical dependence of the normalized spectral density of the characteristics of the traces longitudinal profile irregularities of a constant technological track. Spectral density is conveniently displayed in time units (s^{-1}). Since the argument of this function is the frequency ω (m^{-1}), then in order to switch to time units (s^{-1}), the abscissa of the points of the mentioned spectral density must be multiplied by the speed of modular agricultural unit, and the ordinates on the contrary are divided by this speed.

When comparing the theoretical and experimental normalized spectral densities of the tractor frame vertical vibrations, it can be seen that both processes have a similar nature of the change in the frequency range. This testifies to the correct approach to the development of a mathematical apparatus and assumptions about the nature of forced oscillations. Also, the adequacy of the mathematical model and experimental data is confirmed by the results of testing the null hypothesis about the equality of the theoretical dispersion D_t = 1.18 cm^2 and the experimental D_e = 1.42 cm^2 according to Fisher's F-criterion at a significance level of 0.05.

The frequency spectrum of frame vibrations of the investigated machine and tractor unit is concentrated in range from 0 to 18 s^{-1}(see. Fig. 5), which is consistent with the frequency range of 0...0.35 cm^{-1}, in which the dispersion of fluctuations in the profile irregularities of a constant technological track is concentrated.

The conducted studies confirm that for experimental registration of the initial data of movement and acceleration of agricultural units in the vertical plane, it is sufficient to use modern mobile devices with built-in accelerometer sensors and use an application with direct access to them.

CONCLUSIONS

1. Dependencies of normalized correlation functions of vertical oscillations for the investigated machine and tractor unit during its movement along constant technological track are characterized by a function that contains, along with random components, harmonic ones, which are expressed by attenuating periodic oscillations. The correlation length is approximately 0.16 s, when the velocity of the modular agricultural unit is within 2.2 $m \cdot s^{-1}$ which is equal to 0.35 m. The result obtained is explained by the fact that the main spectrum of fluctuations of the profile irregularities has a periodicity corresponding to the step of the grounding hooks of the wheels tires of the modular agricultural unit and the type of basic tillage.

2. The frequency spectrum of frame vibrations of the investigated machine and tractor unit is concentrated in range from 0 to 18 s^{-1}, which is consistent with the frequency range of 0...0.35 cm^{-1}, in which the dispersion of fluctuations in the profile irregularities of a constant technological track is concentrated.

3. When comparing the theoretical and experimental normalized spectral densities of the tractor frame vertical vibrations, it can be seen that both processes have a similar nature of the change in the frequency range. This testifies to the correct approach to the development of a mathematical apparatus and assumptions about the nature of forced oscillations. Also, the adequacy of the mathematical model and experimental data is confirmed by the results of testing the null hypothesis about the equality of the theoretical dispersion D_t = 1.18 cm^2 and the experimental D_e = 1.42 cm^2 according to Fisher's F-criterion at a significance level of 0.05.

4. The proposed method for the theoretical and experimental determination of the vertical vibrations of a machine-tractor unit can be used in experimental studies of agricultural machines and units.

5. The conducted studies confirm that for experimental registration of the initial data of movement and acceleration of agricultural units in the vertical plane, it is sufficient to use modern mobile devices with built-in accelerometer sensors and use an application with direct access to them.

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