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Mobile machine design through dynamic load simulation on their drive units

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Introduction. The mobile machine design is impossible without considering the vibration parameters of their units. This requires the development of specialized dynamic models that take into account the probabilistic nature of these parameters. The root cause for the occurrence of vibration effects is the profile irregularity of the mobile machine path, and the variability of physicomechanical characteristics of the soil. Problems that consider these features are solved linearly with sufficient accuracy; but in multidimensional dynamical systems, such an approach is unacceptable due to the presence of a large number of interrelationships. The work objective is to conduct a comparative analysis of the efficiency of existing calculation methods of statistical characteristics of uncorrelated external actions as applied to a mobile machine presented as a multidimensional dynamic system with actions having different correlations.

Materials and Methods. External actions in the multidimensional dynamical systems are considered in a matrix form. When calculating statistical characteristics, intercouplings in the spectral density matrices are taken into account. The elements of the main and secondary diagonals are determined; the correlations between the effects are taken into account. These features significantly complicate the calculations. So, to get matrices of uncorrelated actions, the matrix of external actions is reduced to a diagonal form.

Results. A numerical comparison of spectral densities and intensity of the mobile machine oscillations under variation of speeds and nature of the soil fertility microprofile was carried out using various methods of calculation. Certain characteristics of spectral densities and oscillations of mobile machines of agroindustrial complex enabled to develop recommendations on the practical application of the presented dependences for designing this machinery.

Discussion and Conclusions. The results of solving the matrix of spectral densities of external actions by various methods are presented on the diagram of spectral oscillation velocities. The analysis of characteristic curves has shown that the identical results, regardless of the calculation method, are obtained only for machines with weak functional relations under the uncorrelated external action of the soil fertility. For some cases, the resonance machine speeds are set. The effect of irregularities of the soil fertility on the oscillation intensity of the machine units and the dispersion of loads on the units is shown in the graphical representation.

***Keywords**:* multidimensional dynamic system, spectral density matrix, uncorrelated external influences, inverse matrix, attached matrix.

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Introduction. When designing reliable mobile equipment, both static dynamic loads should be considered. Vibrations of the machine and its components affect significantly the characteristics of dynamic loads. Accounting and determination of vibration parameters require the development of specialized dynamic models that consider these parameters as regards to probabilistic analysis. The root reason for the vibration effects is due to the uneven profile of the mobile machine path and the inconsistency of the physical and mechanical characteristics of the agricultural background. Problems that consider these features are solved linearly with sufficient accuracy, which is unacceptable when solving multidimensional dynamical systems with a large number of interconnections.

Materials and Methods. Quality of the technological process performed by a mobile agricultural machine is affected by both the characteristics of its working bodies [1–5] and the characteristics of the undercarriage system [6, 7], as well as the microrelief of the agricultural background [8, 9]. In general, external actions on a machine are considered as a system with *n* functions. The processes of changing the microroughness of the path (or changing the soil density) are denoted as functions $q_1(t) \dots q_n(t)$ [9, 10].

If the statistical description of external actions admits a stochastic orthogonal representation, then the following equation is valid:

$$q_i(t) = m\left[q_i(t)\right] + \int_{-\infty}^{\infty} Q_i(\omega) \cdot \phi_i(t,\omega)\, d\omega,$$

where $Q_i(\omega)$ is a system of random functions ω; $\varphi_i\ (t,\omega)$ is a system of nonrandom functions t and parameter ω; $m\ [q_i(t)]$ is mathematical expectation.

Mobile agricultural machines are systems with delayed actions [2, 6, 9], which are characterized by many parameters of uneven field microrelief or soil hardness [2, 8, 9]. These are one-type parameters, and they can be shifted in time t_0. In addition, the design of the machine (front and rear axle wheels) affects the relationship between the actions. Given these features and the assumption that the mathematical expectation of external actions is zero, the matrix of spectral densities of external actions is described as follows [11, 12]:

$$S_q(\omega, j\omega) = \begin{Vmatrix} S_h(\omega) & S_h(\omega)e^{-j\omega t_0} & c_{13}S_{h\psi}(j\omega) \\ S_h(\omega)e^{j\omega t_0} & S_h(\omega) & c_{23}S_{h\psi}(j\omega) \\ c_{31}S_{\psi h}(j\omega) & c_{32}S_{\psi h}(j\omega) & S_\psi(\omega) \end{Vmatrix}, \tag{1}$$

where $c_{13} = t; c_{23} = e^{-j\omega t_0}; c_{31} = 1; c_{32} = e^{j\omega t_0}$ — for front drive axle; $c_{13} = e^{-j\omega t_0}; c_{22} = 1; c_{31} = e^{j\omega t_0}; c_{32} = 1$ — for rear drive axle.

To simplify the calculation of statistical characteristics, we reduce the matrix to a diagonal form to obtain a matrix of uncorrelated external actions. We introduce the characteristic matrix and reduce the matrix (1) to the form:

$$S_q(\omega, j\omega) - \lambda(j\omega) \cdot E = \begin{Vmatrix} S_h(\omega) - \lambda(j\omega) & S_h(\omega)e^{-j\omega t_0} & c_{13}S_{h\psi}(j\omega) \\ S_h(\omega)e^{j\omega t_0} & S_h(\omega) - \lambda(j\omega) & c_{23}S_{h\psi}(j\omega) \\ c_{31}S_{\psi h}(j\omega) & c_{32}S_{\psi h}(j\omega) & S_\psi(\omega) - \lambda(j\omega) \end{Vmatrix}, \tag{2}$$

where λ is a characteristic function; E is an identity matrix.

The characteristic equation can be represented as:

$$a\lambda^3(j\omega) + b\lambda^2(j\omega) + c\lambda(j\omega) + d = 0. \tag{3}$$

The characteristic functions $\lambda_1(j\omega), \lambda_2(j\omega), \lambda_3(j\omega)$ were defined using Cardano formulas [13].

The matrix of transition to a new basis constructed from the coordinates of the vectors $\lambda_i(j\omega)$ (at *i*=1, 2, 3) defined from the equation (3), has the form:

$$T(j\omega) = \begin{Vmatrix} \eta_{11} & \eta_{21} & \eta_{31} \\ \eta_{12} & \eta_{22} & \eta_{32} \\ \eta_{13} & \eta_{23} & \eta_{33} \end{Vmatrix}. \tag{4}$$

In this case, the inverse matrix has the form:

$$T^{-1}(j\omega) = \frac{\tilde{T}(j\omega)}{\left|T(j\omega)\right|}, \tag{5}$$

where $\tilde{T}(j\omega)$ is an adjoint matrix; $\left|T(j\omega)\right|$ is a matrix determinant.

The desired matrix was determined from the expression:

$$S_d(j\omega) = T^{-1}(j\omega)\cdot S_q(\omega, j\omega)\cdot T(j\omega) = diag\left\|S_1(j\omega)\cdot S_2(j\omega)\cdot S_3(j\omega)\right\|, \tag{6}$$

where S_1, S_2, S_3 are spectral densities of uncorrelated effects of complex-variable functions.

Finding the diagonal matrix (6) is simplified through solving a planar problem. In this case, external actions can be represented as:

$$S_q(\omega, j\omega) = \begin{Vmatrix} S_h(\omega) & S_h(\omega)e^{-i\omega t_0} \\ S_h(\omega)e^{i\omega t_0} & S_h(\omega) \end{Vmatrix}. \tag{7}$$

Then the characteristic matrix is determined from the expression:

$$S_q(\omega, j\omega) - \lambda(\omega)\cdot E = \begin{Vmatrix} S_h(\omega) - \lambda(\omega) & S_h(\omega)e^{-i\omega t_0} \\ S_h(\omega)e^{i\omega t_0} & S_h(\omega) - \lambda(\omega) \end{Vmatrix}. \tag{8}$$

In turn, the characteristic equation can be represented as:

$$\lambda^2(\omega) - 2S_h(\omega)\cdot\lambda = 0. \tag{9}$$

From which, the roots of the equation are: $\lambda_1(\omega) = 0, \lambda_2(\omega) = 2S_h(\omega)$.

At the root $\lambda_1(\omega) = 0$, the system of equations for determining the coordinates of the eigenvectors has the following form:

$$S_h(\omega)\eta_{11}(j\omega) + S_h(\omega)e^{-j\omega t_0}\cdot\eta_{12}(j\omega) = 0. \tag{10}$$

Given $\eta_{11} = e^{-j\omega t_0}$, we find $\eta_{12}(j\omega) = 1$.

At root $\lambda_2(\omega) = 2S_h(\omega)$, we get the system of equations:

$$\begin{cases} -S_h(\omega)\cdot\eta_{21}(j\omega) + S_h(\omega)e^{-j\omega t_0}\cdot\eta_{22}(j\omega) = 0 \\ S_h(\omega)^{j\omega t_0}\cdot\eta_{21}(j\omega) + S_h(\omega)\cdot\eta_{21}(j\omega) = 0 \end{cases}. \tag{11}$$

Then the matrix of transition to a new basis takes the following form:

$$T_1(j\omega) = \begin{Vmatrix} e^{-j\omega t_0} & e^{j\omega t_0} \\ -1 & e^{2j\omega t_0} \end{Vmatrix}. \tag{12}$$

Through transforming the expression (8), we find spectral densities of uncorrelated effects:

$$S_1(j\omega) = S_h(\omega)\cdot(1 + e^{-j\omega t_0}) = 0.$$

$$S_2(j\omega) = S_h(\omega)\cdot(1 + e^{j\omega t_0}) = 0. \tag{13}$$

If we assume that the profile of the agricultural background in the longitudinal and cross section is determined by uncorrelated random processes [8, 9], then we can imagine the third element of the diagonal matrix as $S_\omega(\omega)$. In this case, the matrix (13) takes the form:

$$S_d(j\omega) = diag\left\|S_h(\omega)\cdot(1 + e^{-j\omega t_0});\quad S_h(\omega)\cdot(1 + e^{j\omega t_0});\quad S_\psi(\omega)\right\| \tag{14}$$

Spectral densities of vibrations were determined through solving the matrix (1), together with the matrix (14) and with account of formulas describing uncorrelated actions. The result is the expression:

$$S_z(\omega) = S_h(\omega)\left[\Phi_{11}^2(\omega) + \Phi_{12}^2(\omega)\right] = 0. \tag{15}$$

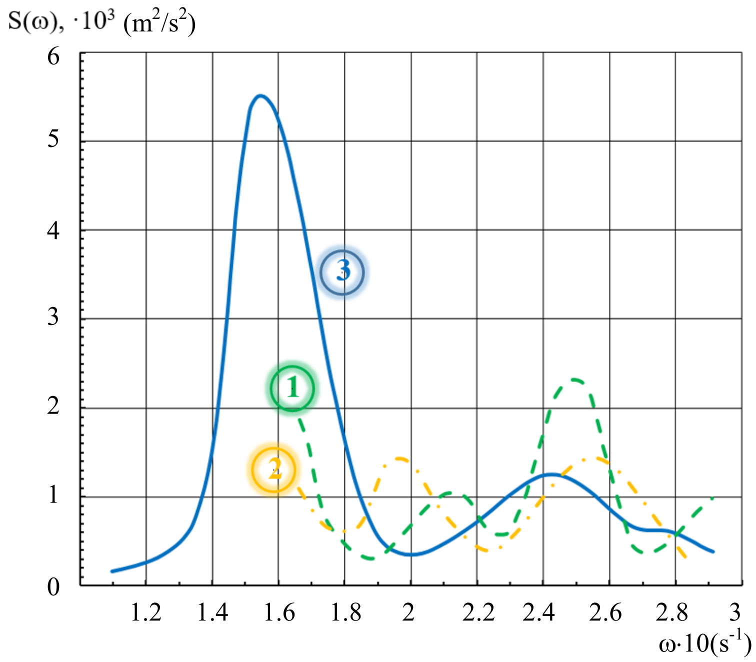

Fig.1 Spectral velocities of vibrations in the solution using:
curve 1— matrix (1); curve 2 — matrix (6); curve 3—matrix (15).

Research Results. Fig. 1 shows graphs of spectral densities of vertical velocities of the front part of the thresher of “Vector” line harvester. Obviously, the dynamic parameters of the machine affect the vibration spectrum (Fig. 1). The narrowband spectrum is typical for conditions of close coincidence of the frequencies of natural vibrations of the combine axles with the reaper (Fig. 1). The width of the spectrum is also affected by the delay in the actions of the wheels of the combine axles.

The results of calculating the intensity of vibrations using matrices (1), (6), (15) are diagrammatized in Fig. 2, which confirms the dependence of functional relationships in the machine on the nature of external actions.

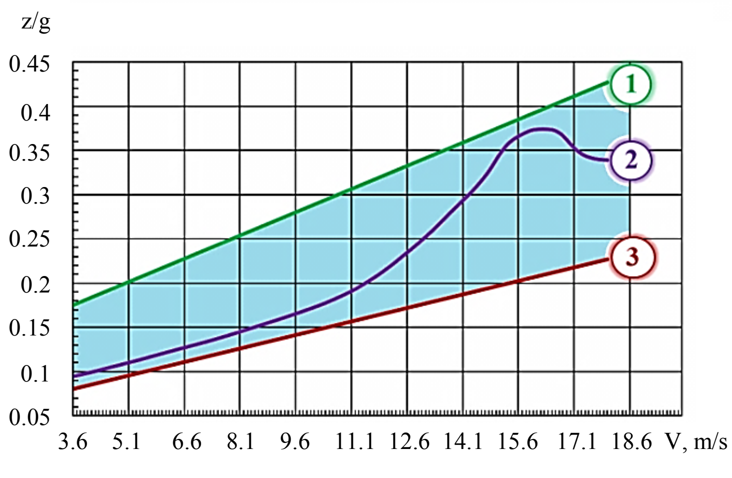

Fig. 2. Diagrams of vibration intensity when the machine moves along microprofile with different nature of irregularities:
1 and 2 — along the furrow; 3 — across the furrow

Solving the systems, which are uncorrelated external actions on a moving machine with weak functional relationships, gives close results regardless of the methods used.

Identical results, when using various calculation methods, are obtained only for machines with weak functional relationships when moving along the field microprofile that generates an uncorrelated external action.

The dynamic characteristics of the combine harvesters were evaluated according to the following formula:

$$W_{ke} = \frac{1}{\pi} \int_{\omega_1}^{\omega_2} S_{ke}(\omega) \cdot d\omega , \tag{16}$$

where ω_1, ω_2 are spectrum frequency boundaries.

The vibration intensity for various conditions determined using the formula (16), is presented in Fig. 3.

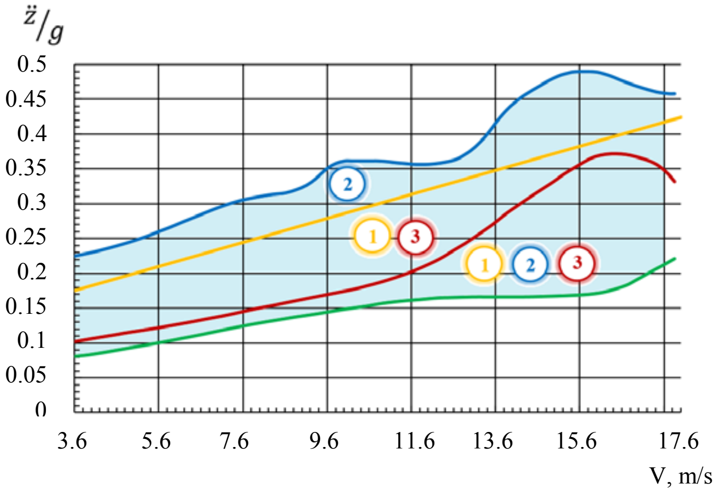

Fig. 3. Engineering assessment results of the harvester dynamics

Fig. 3 shows the dependence of overloads $\ddot{z}/g$ on the combine harvester velocity. Obviously, the different spectral composition of the irregularities of the agricultural background microprofile affects the intensity of vibrations of the machine nodes. There are resonant speeds in the range from 10 to 15 km/h. The graphical dependences obtained (Fig. 2, 3) provide estimating the load spread on the units.

The shaded area illustrates their scattering and enables to estimate the coefficients of variation of $V(z)$. The table shows parameters of the distribution of loads at medium speeds of the machines [2].

Table 1

Dynamic load parameters of mobile machines of agroindustrial complex

Machine type	Work mode	Motion speed m/s	$z_{ск}/g$
Combine harvester Vector	operational	0.840	0.332
	transport	2.781	0.835
Tractor K-700A, trailer 2 PTS-4	operational	3.352	0.474
	transport	8.323	0.510
Tractor T-150A, combine KKU	operational	1.247	0.364
	transport	3.527	0.382
Tractor T-150A, plow PR-2,7	operational (tillage)	0.752	0.346

Results and Discussion. The analysis of the calculation results of the spectral densities of vibrations according to formulas (1), (6), (15) is diagrammatized in Fig. 2, 3. From the graphical dependences, it can be seen that the spectrum of the effects of the loads and their dynamics affect the calculation error.

The calculation of dynamic multidimensional systems and the assessment of machine vibrations are automated and performed using a specialized software product[1].

[1] Groshev LM, Partko SA, Lukonin AYu. Calculation of random vibrations of the housing of Don line combine harvester. Certificate of software registration no. 2012614015 Russian Federation. Applicant and proprietor, FSBEI of Higher Education “Don State Technical University”. No. 2012611617; March 7, 2012; publl. 04.28.2012.

The program is used to select vibration parameters of the contours and units of mobile agricultural machines, to calculate the smoothness of combine harvesters, to design machine parts [14], and to assess the working conditions of the machine operator.

Before using a software product, you should select a dynamic model first, then to set the design parameters of the machine and its units, and to determine the mass-geometric and elastic-dissipative characteristics of the system.

Conclusions. The expressions (1), (6), (15) are acceptable for the design calculations of spectral densities of impacts on machine components. The use of the formula (6) is unacceptable when designing machines with a mode of movement along irregularities of an agricultural background with a low-frequency spectral composition and for machines with a low correlation of vibrations of the undercarriage and the steering.

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Claimed contributorship

S. A. Partko: basic concept formulation, research objectives and tasks setting; development of the mathematical model; computational analysis; text preparation; formulation of conclusions. L. M. Groshev: academic advising; analysis of the research results; correction of the text and conclusions. A. N. Sirotenko: implementation of the experimental validation; processing of the results; calculations; correction of the text and conclusions.

All authors have read and approved the final manuscript.