Development of a mathematical model of the oscillatory system of agricultural mobile power equipment with attachments for the creation of their adaptive springing systems

Zakhid Godzhaev[1*], *Sergey* Senkevich[1], *Ivan* Malakhov[1], and *Sergey* Uyutov[1]

[1]Federal State Budgetary Scientific Institution "Federal Scientific Agroengineering Center VIM", 1st Institute passage, house 5, 109428 Moscow, Russia

Abstract. A mathematical model of oscillations of a mobile energy means (MEM) is presented and investigated. The proposed MEM oscillation model makes it possible to determine the positions of the MEM center of mass points in various situations on a support base (agrophone) with a different microprofile. Differential equations have been compiled for computer simulation. The solution of differential equations describing the oscillations of the MEM during its movement in a compound with attachments, as well as a computational experiment-simulation modeling were performed in the software complexes Mathcad and MATLAB Simulink. The initial data used are the mass-dimensional and elastic-damping properties of the structural elements of the MEM, based on the TK-3-180 tractor, obtained by calculation and experiment and a real support base (agrophone) with a known micro- and macro profile. The model makes it possible to study the dynamic processes of the oscillatory system "Support base (agrophone) – running system – machine frame with attachments – cab". The results of computer simulation modeling are presented – graphs showing fluctuations of sprung and unsprung masses of MEM when moving on different backgrounds.

1 Introduction

The choice of methods for modeling multi-mass oscillatory systems of agricultural mobile power equipment is based on the choice of efficiency criteria when creating adaptive running systems.

Real complex systems can be investigated using two types of mathematical models: analytical and simulation. In analytical models, the behavior of complex systems is recorded in the form of some functional relations or logical conditions. However, phenomena in complex systems are so complex and diverse that analytical models become too rough an approximation to reality, therefore, simulation modeling (SM) should be used. In SM, the behavior of system components is described by the choice of algorithms that implement situations that arise in a real system. Mathematical modeling is used to describe

* Corresponding author: fic51@mail.ru

and study real processes and phenomena using mathematical models. This makes it possible to simplify complex systems, identify patterns and predict the behavior of the system in various conditions.

An analytical model is a mathematical model that can be solved analytically, that is, using formulas and equations. It allows you to get an accurate solution and a deeper understanding of the system, but can only be applied in cases where the system has an analytical solution.

A simulation model is a mathematical model that is used to simulate a real system on a computer. It allows you to experiment with the system in various conditions to determine its behavior and identify possible problems or improvements. The simulation model can be applied in cases where an analytical solution is impossible or too difficult.

The dynamics of the tractor is actually always oscillatory, estimated by the intensity of vertical, longitudinal and angular vibrations of the sprung masses and depends not only on the basic design parameters of the engine, transmission, suspension, tires, but also on the parameters of the running system.

In this paper, the relevance of the problem of increasing the efficiency of the adaptive tractor springing system is substantiated, one of the stages of solving which is an adequate simulation model.

Based on this, the purpose of this work is to determine the parameters of structural elements that take into account the probabilistic nature of functioning, structural features of varieties of adaptive springing system (ASS) for their study. To achieve this goal, it is necessary to solve the following tasks:

1. To conduct an analytical review of the work on the calculation of the parameters of the oscillation cycle, the formation and evaluation of the performance of the ASS.
2. Selection of the formation modeling method.
3. Development of a mathematical model of the ASS.

The development of a mathematical model includes the development of a design scheme, dynamic oscillations of the MEM with attached technological equipment on the front and rear axles [1]. The design scheme includes the masses of the bridges (front and rear), the skeleton of the mobile power equipment, the masses of the cab and the masses of technological attachments, also stiffness and damping properties are included in the design scheme. The damping and elastic characteristics of the springing of the front axle (which has a pneumatic cushion as an elastic element), the rear axle, the tires of the front and rear axles, and the springing of the cab are also taken into account. Based on the results of solving systems of differential equations that make up a mathematical simulation model of a dynamic system, we obtain mass displacements and natural frequencies of the oscillatory system. In the future, this mathematical model will be included in the general software and algorithmic complex for determining control actions for the MEM springing system. The ASS implies operational control of the stiffness and damping properties of the springing element (air cushion) during the movement of the MEM.

2 Review of works on the research topic

There are many studies devoted to the dynamics of the movement of agricultural MEM. The authors of the work [1] developed a dynamic model of the power transmission, analyzed the processes of gear shifting and developed coordinated strategies for managing these processes with the replacement of several clutches during tractor field work. The reduction of dynamic loads on suspension and power transmission elements has a positive effect on the reliability of the entire tractor, which is confirmed by studies [2-4.]. Effective interaction of the chassis of the machine with the ground surface also helps to increase productivity and reduce fuel consumption [5-8].

Papers [9-11] are devoted to the issue of modeling dynamic processes of mobile machines. In them, the authors considered the formation of the basic operational properties of mobile wheeled vehicles, developed software tools and methods for determining the parameters of the suspension elements during bench tests, including tests of mobile equipment with an electronic control system [12,13].

A large number of studies have been conducted to study and create an effective system for springing mobile machines [14,15]. In these works, the authors investigated the effect of vibrations with a wide spectrum of the frequency range. They made the adjustment so as to ensure the smooth running of the mobile vehicle under the required driving conditions. According to the authors, this largely depends on the dynamic behavior of the car body, which is subjected to a combination of vertical, longitudinal-angular and transverse-angular vibrations during operation. It is possible to reduce these fluctuations by using special structural elements of the suspension [16-20].

The conducted review shows the relevance of research in the field of reducing the vibration load of MEM and mobile machines operating in heavy field and road conditions.

3 Methods

To model the oscillations of the MEM, the authors use an equivalent calculation scheme of the oscillatory system, which is described in detail, for example, in [21-24]. The equivalent system of vibrations of the MEM during its movement is reduced to a system with concentrated masses connected to elastic elements without mass, including the elasticity of the suspension and shock absorbers structural elements. The equivalent oscillation system also takes into account the damping characteristics of the masses and compounds. As external disturbing factors of the dynamic system, the impact from the support surface is taken. Since in some cases the attachments have rigid connections with the skeleton of the MEM, its mass is summed up with the mass of the frame.

4 Results

The object of the simulation is the ASS springing system adopted tractor traction class 3 “Agromash TK-3-180”. The tractor has a classic layout scheme, is designed to perform technological work in soil-climatic zones with a temperate climate for basic and pre-sowing tillage (plowing, non-fall loosening, harrowing, continuous cultivation), sowing of grain, harvesting and transport operations, stubble peeling and soil disking, fertilization, snow retention, moisture closure, etc. other works in the unit with mounted, semi-mounted and trailed machines and tools.

The MEM oscillation system is shown in Figure 1. To expand the understanding of the dynamic characteristics of the system, we have introduced an additional rear axle springing system into the design scheme. A rod sprayer of herbicides and pesticides weighing 750 kg was used as attachments.

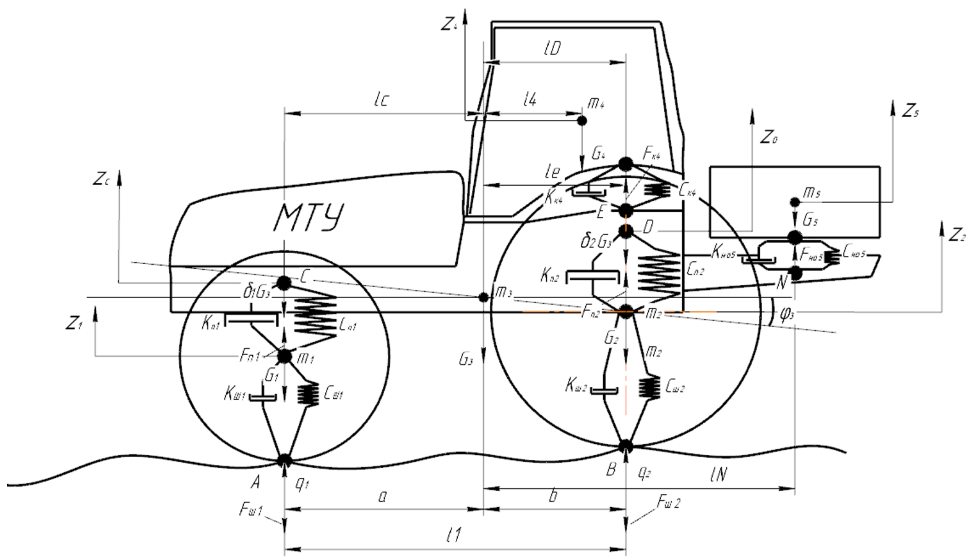


Fig. 1. Design scheme of the oscillating system of the tractor

When compiling this system, mathematical models from the theory of tractor movement were used [21-23], the following designations were introduced:

$C_{s1} -$ front tire stiffness coefficient; $C_{s2} -$ rear tire stiffness coefficient; $C_{p1} -$ front suspension stiffness coefficient; $C_{p2} -$ rear suspension stiffness coefficient; $C_{p4} -$ cab suspension stiffness coefficient; $m_1 -$ front axle weight; $m_2 -$ rear axle weight; $m_3 -$ the weight of the frame; $m_4 -$ the weight of the cab; $m_5 -$ the weight of the attachments; $C_{s1} -$ damping coefficient of the front tire; $\mathrm{c}_{s2} -$ damping coefficient of the rear tire; $k_{p1} -$ damping coefficient of the front axle springing system; $k_{p2} -$ damping coefficient of the rear axle springing system; $k_{k4} -$ damping coefficient of the cab springing system; $k_{k5} -$ damping coefficient of the attachment springing system; $J_3 -$ moment of inertia of the tractor frame; $a -$ distance from the center of mass of the tractor to the front axle; $b -$ the distance from the center of mass of the tractor to the rear axle; $l_c -$ the distance from the attachment point of the front axle springing system to the frame to the center of mass; $l_D -$ the distance from the attachment point of the rear axle springing system to the frame to the center of mass; $l_N -$ the distance from the upper point of the attachment point of the cab springing system to the center of mass of the tractor; $l_E -$ the distance from the center of mass of the cab to the center of mass of the tractor.

The variables in the system are the following values of mass displacement: Z_1, Z_2, Z_3, Z_4.

A mathematical model of a 4-mass dynamic system, taking into account the springing of the front and rear axles, is given below:

$$
\begin{aligned}
&m_1\ddot{Z}_1 = -G_1 - F_{s1} + F_{p1}\\
&m_2\ddot{Z}_2 = -G_2 - F_{s2} + F_{p2}\\
&m_3\ddot{Z}_3 = -G_3 + F_{p1} + F_{p2} + F_{k4} - G_4\\
&I_3\ddot{\varphi}_3 = G_1\cdot a - F_{s1}\cdot a - F_{p1}\cdot l_c - G_2\cdot b + F_{s2}\cdot b + F_{p2}\cdot l_D + G_4\cdot l_4 - F_{k4}\cdot l_E\\
&m_4\ddot{Z}_4 = -G_4 + F_{k4}
\end{aligned}
\tag{1}
$$

where

$$
\begin{gathered}
F_{s1} = 2C_{s1}(Z_1 - q_1) + 2k_{s1}(\dot{Z}_1 - \dot{q}_1) \\
F_{s2} = 2C_{s2}(Z_2 - q_2) + 2k_{s2}(\dot{Z}_2 - \dot{q}_2) \\
F_{p1} = C_{p1}(Z_c - Z_1) + k_{p1}(\dot{Z}_c - \dot{Z}_1) \\
F_{p2} = C_{p2}(Z_d - Z_2) + k_{p2}(\dot{Z}_d - \dot{Z}_2) \\
F_{k4} = C_{k4}(Z_E - Z_3) + k_4(\dot{Z}_E - \dot{Z}_3) \\
Z_c = Z_3 + a\varphi_3 \\
Z_d = Z_3 + b\varphi_3 \\
Z_E = Z_3 + l_E\varphi_3
\end{gathered}
\qquad (2)
$$

Changing the coordinates of the microprofile. Accordingly, under the front and rear wheels of the tractor have the following dependencies [18]:

$$
q_1 = \frac{1}{2} \cdot H_{11} \cdot \sin(2\pi \frac{x(t)}{S_{11}}) + \frac{1}{2} \cdot H_{12} \cdot \sin(2\pi \cdot \frac{x(t)}{S_{12}})
$$

$$
q_2 = \frac{1}{2} \cdot H_{21} \cdot \sin(2\pi \frac{x(t)}{S_{21}}) + \frac{1}{2} \cdot H_{22} \cdot \sin(2\pi \cdot \frac{x(t)}{S_{22}})
$$

H_{11}, H_{12} – the value of the mathematical expectation of the height of the irregularities of the longitudinal profile of the support base under the front wheels of the tractor;

H_{21}, H_{21} – the value of the mathematical expectation of the height of the irregularities of the longitudinal profile of the support base under the rear wheels of the tractor;

S_{11}, S_{12} – the value of the mathematical expectation of the length of the profile irregularity under the front wheels of the tractor;

S_{21}, S_{22} – the value of the mathematical expectation of the length of the profile irregularity under the rear wheels of the tractor;

x(t) – the value of the track coordinate of the profile under the tractor wheels.

Quantitative characteristics of the microprofile of roads and fields are determined by us on specific backgrounds of technological agricultural operations.

The load (elastic) characteristics of the pneumatic element of the ASS are shown in Figure 2 (*on the left* – rebound, *on the right* – compression). The characteristic is used as input data for simulation modeling of dynamic processes.

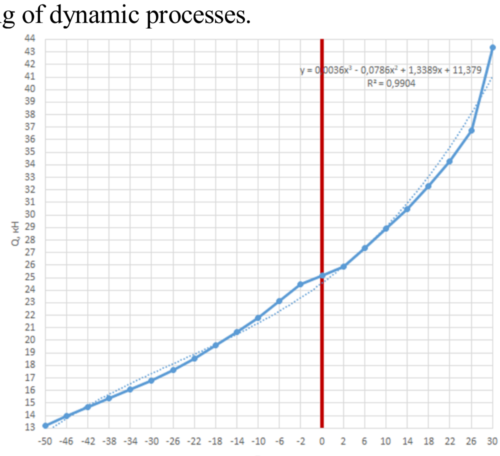


Fig. 2. Load characteristic of the pneumatic element

With the help of MATLAB Simulink and Mathcad software complexes, calculations of the dynamic characteristics of the oscillatory system were carried out according to the above calculation scheme (Figure 1).

5 Discussion

The graph of the dependence of the microprofile of the support base, obtained by formulas (3) and (4), on the longitudinal coordinate is shown in Fig. 3.

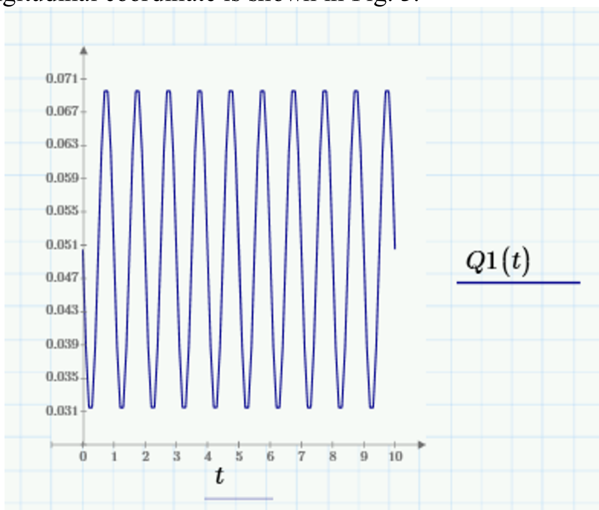
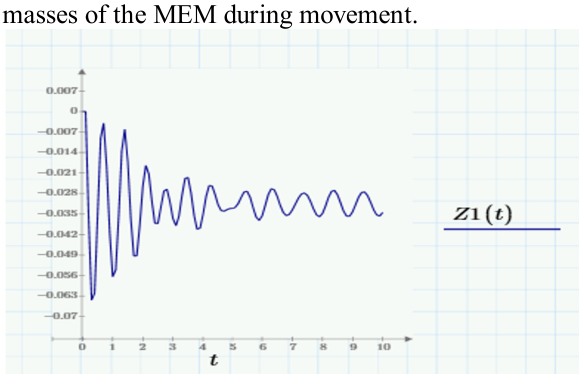
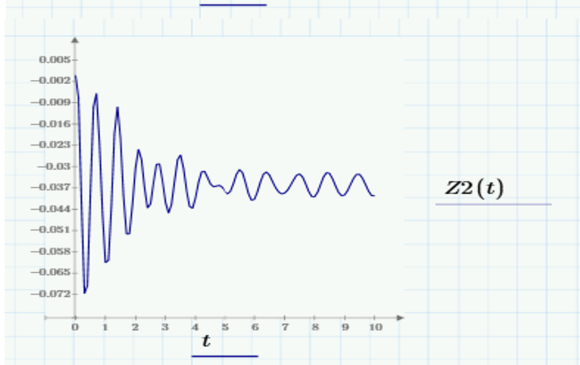


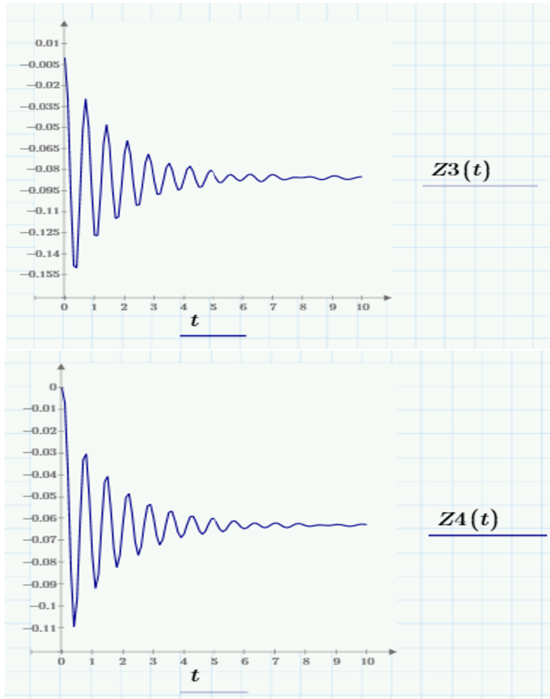
Fig. 3. Changing the coordinate of the micro profile of the support base

Figures 4 and 5 show the results of simulation modeling − vertical and angular movements of the masses of the MEM during movement.





 https://doi.org/10.1051/e3sconf/202341302042



c) *d)*

Fig. 4. Vertical movements of the masses of the MEM during its movement, respectively: *a)* – z_1; *b)* – z_2; *c)* – z_3 ; *d)* – z_4;

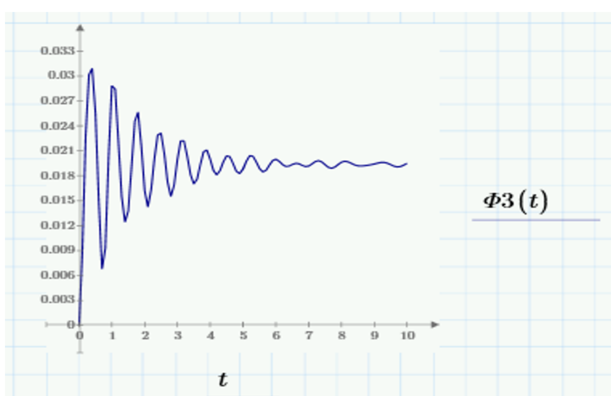


Fig. 5. Angular displacement of the center of mass of the sprung mass (skeleton) of the mobile energy vehicle during its movement

6 Conclusion

1. The presented mathematical simulation model of MEM oscillations makes it possible to determine the magnitude of the movements of the oscillating masses of various tractor masses.
2. The results of computer simulation modeling (Fig. 4, 5) clearly demonstrate the fluctuations of the masses of the energy medium when it moves along an uneven support base. The center of mass of the sprung mass of the power vehicle (skeleton) is vibro-loaded

less (moving z_3) than the sprung masses of the front (moving z_1) and rear (moving z_2) axles, this indicates the effectiveness of the applied springing system.
3. The presented model of dynamic vibrations of the MEM during movement can be used to develop optimal elastic-damping characteristics of the ASS in order to reduce the vibration load of the MEM structural elements when performing agricultural work.

Acknowledgments

The research was carried out at the expense of a grant from the Russian Science Foundation — Agreement No. 23-29-00289 from January 13, 2023, https://rscf.ru/project/23-29-00289 /.

References

1. V. V. Ayupov, Mathematical modeling of technical systems: textbook, Ministry of Agriculture of RF, Federal state budgetary education. institution of higher education “Perm State Agricultural Academy named after D.N. Pryanishnikov”. Perm: CPI “Prokrost”, ISBN 978-5-94279-337-1, 242 (2017)
2. B. Li, Coordinated control of gear shifting process with multiple clutches for power-shift transmission, Mech. Mach. Theory, **140**, 274-291 (2019)
3. N. K. Kuznetsov, Reducing of dynamic loads of excavator actuators J. of Physics: Conference Series, IOP Publishing, **1**, 012075 (2019) https://doi.org/10.1088/1742-6596/1210/1/012075
4. Z. A. Gojaev, V. I. Pryadkin, A.V. Artemov, P. A. Kolyadin, Evaluation of the influence of tire parameters on the controllability of the car, Automotive industry **2**, 14-19 EDN NUYPUI (2023)
5. Z. A. Gojaev, The use of adaptive running systems for springing MES to reduce vibration activity from the support surface, Fundamental and applied problems of engineering and technology **6(356)**, 138-142 (2022)doi 10.33979/2073-7408-2022-356-6-138-142
6. O. I. Polivaev, O. S. Vedrinsky, N. M. Derkanosova, Increasing the durability of tractor coupling due to the elastic-friction damper, Science and education in modern conditions: materials of the international scientific conference, under the general editorship: Voronezh: Voronezh State Agrarian University named after Emperor Peter **I**, 226-230 (2016)
7. V. N. Loy, A. O. Germanovich, Evaluation of the vibration load of the workplace of the operator of a mobile chopping machine, Proceedings of BSTU. No. 2. Forestry and woodworking industry 2(175), 3-7 (2015)
8. I. Melikov, *Traction and energy efficiency tests of oligomeric tires for category 3 tractors*, IOP Conference Series: Earth and Environmental Science, 403, 012126 (2019) doi: https://doi.org/10.1088/1755-1315/403/1/012126
9. V. Dygalo, *Formation of basic performance properties of wheeled vehicles in braking mode*, Transportation Research Procedia : 14, Saint Petersburg, 130-135 (2020) doi 10.1016/j.trpro.2020.10.016.
10. V. V. Shekhovtsov, Technology of creation of three-dimensional model of tractor transmission in program package "universal mechanism, Lecture Notes in Mechanical Engineering, 9783319956299, 2017-2025 (2019) doi 10.1007/978-3-319-95630-5_217.
11. E. A. Fedyanov, N. S. Sokolov-Dobrev, M. V. Ljashenko, Method of determining operation parameters of stand tests of vehicle suspension elements under conditions of

ultra-low temperatures, Journal of Physics: Conference Series, Tomsk, 032126 (2018) doi 10.1088/1742-6596/1015/3/032126.

12. V. Shekhovtsov, M. Lyashenko, P. Potapov, *Calculated and experimental tests of dynamic vibration isolators for use in the suspension system of the traction vehicle cabin*, IOP Conference Series: Materials Science and Engineering : Design Technologies for Wheeled and Tracked Vehicles, MMBC 2019, Moscow, Moscow: Institute of Physics Publishing, 012022 (2020) doi 10.1088/1757-899X/820/1/012022.
13. D. Ilyushin, Ye. A. Salykin, V. Shekhovtsov, *Special aspects of the test of ATV equipped with the electronic engine management system Continental M3C on a dynamometer test bench*, IOP Conference Series: Materials Science and Engineering : Design Technologies for Wheeled and Tracked Vehicles, MMBC 2019, Moscow, Institute of Physics Publishing, 012011 (2020) doi 10.1088/1757-899X/820/1/012011.
14. P. J. T. Venhovens, The Development and Implementation of Adaptive Semi-Active Suspension Control*, Veh. Syst. Dyn. 23(1), 211–235 (1994)
15. O. Prentkovsky, R. Pechelyunas, Dynamics of transcontinental distribution in memory, Materials of the International Conference RelStat'04. Part 3. Transport and telecommunications **6(3)**, 407 (2005)
16. S. Senkevich, V. Bolshev, E. Ilchenko, P. Chakrabarti, M. Jasiński, Z. Leonowicz, M. Chaplygin. Elastic Damping Mechanism Optimization by Indefinite Lagrange Multipliers, IEEE Access, **9**, 71784-71804 (2021) doi: 10.1109/ACCESS.2021.3078609
17. R. M. Chalasani, Ride performance potential of active suspension systems - Part II: Comprehensive Analysis Based On A Full-Car Model. Am. Soc. Mech. Eng. Appl. Mech. Div. AMD. **80**, 205–234 (1986)
18. Z. A. Godzhaev, S. E. Senkevich, V. A. Zubina, T. Z. Godzhaev, *Determination of the significance of quality criteria and functional limitations affecting the effectiveness of robotization of mobile energy means in crop production*. IOP Conf. Ser.: Earth Environ. Sci., 1138, 012045 (2023) doi: 10.1088/1755-1315/1138/1/012045
19. R. A. Williams, Electronically controlled automotive suspensions Comput. Control Eng. J., **5(3)**, 143–148. (1994)
20. C. Gohrle, et al., *Design and Vehicle Implementation of Preview Active Suspension Controllers*, IEEE Trans. Control Syst. Technol., 22(3), 1135–1142 (2014)
21. A. A. Khachaturov, Dynamics of the road – tire – car–driver system, Moscow, Mechanical Engineering, 535 (1976)
22. Z. A. Gojaev, Vibration protection of the hydraulic system of springing mobile machines with the use of active regulation by a neural network , Tractors and agricultural machines, **4**, 43-49 (2019) doi 10.31992/0321-4443-2019-4-43-49. – EDN OZQAPF.
23. G. M. Kutkov, Theory of tractor and automobile: textbook for universities, Moscow, Kolos, 271-279 (1996)
24. B. A. Afanasyev, B. N. Belousov, L. F. Zheglov, Designing four-wheel drive wheeled vehicles: Textbook for universities: P79 In 3 t. t., etc.; Moscow, Publishing House of Bauman Moscow State Technical University, 432 (2008)