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THE USE OF ADJUSTABLE DAMPING DEVICES FOR INCREASING TECHNICAL LEVEL OF GROUND ROBOTIC COMPLEXES EQUIPPED WITH A MANIPULATOR

A dynamic model of the manipulator of the robotic complex was developed on the basis of the conducted experimental studies. The concept of determining the dynamic characteristics of the mechanical system is proposed according to the results of the oscillation analysis. The algorithm is supplemented with modules considering possibility of using controlled damping devices.

The constituent parts of the model represent the mechanical devices of the manipulator, in particular connections, rotary assemblies and damping devices. The model contains all the connections between the modules, which allows you to study the dynamic parameters during the operation of the mechanism. Differential dependencies for the implementation of the mathematical model, which includes the subsystem of dynamic damping of vibrational oscillations of the manipulator, are proposed. These dependencies reveal the essence of the oscillatory processes of the mechanical system in full. Guided damping devices introduced into the model allow to control parameters in order to increase the accuracy of the mechanism.

The mathematical model is implemented via a software module that takes into account the impact working processes that occur in the connections and rotary assemblies of the mechanical system of the robotic complex.

The algorithm involves the use of a mechatronic system equipped with feedback sensors to control the manipulator. Controlled damping devices make it possible to increase the technical level and improve the dynamic characteristics of the mechanical system. Damping of oscillations by a mechatronic system with feedback was investigated and the influence of damping of oscillations on accuracy parameters when moving a robotic complex on an uneven surface was determined.

The paper presents the results of modeling an adjustable damper as part of a moving mechanical system. The innovative device uses a magnetorheological fluid as a working fluid, which allows you to control it with the help of electrical impulses. The conducted experimental studies made it possible to obtain key indicators and its operating characteristics of the damper. Based on these results, dependencies, which determine the control laws of a damper that uses a magnetorheological fluid, are proposed.

***Keywords**: ground robotic complex, manipulator, mechatronic system, mathematical modeling, dynamic characteristics, damper, accuracy.*

Formulation of the problem. Modern ground robotic complexes have a high carrying capacity, accuracy and speed. They are able to move on uneven surfaces and interact with objects with the mechanism equipped with an advanced control system [1]. Objects can be moved with a mobile or stationary robotic complex. In the first case, the process requires ensuring high dynamic characteristics of the manipulator.

To expand the possibilities of robotic applications, the complexes can use the progressive design of the manipulator, which provides necessary accuracy and dynamic characteristics, as well as the control system built on the basis of adaptive algorithms.

However, to improve the dynamics of mechanical systems, it is necessary to develop their accurate mathematical models. Taking into account the peculiarities of the work and constructive implementation of the mechanical system allows to increase the accuracy of the mechanism. Features of the manipulator's operation are taken into account using a detailed mathematical model, which is included in the control system. The algorithm allows to use the advantages due to the presence of feedback sensors to improve the parameters of the mechanical system. When developing a mathematical model of the manipulator, it is necessary to carry out a detailed study of the system, take into account the peculiarities of the work processes of connections and rotary assemblies and their constructive implementation.

To achieve the best dynamic characteristics of robotic complexes, it is most appropriate to use controlled damping devices. In order to solve this problem, it is necessary to study the regulatory processes that have the greatest impact on the accuracy of technological operations. The relevance of research is confirmed by the wide application of robotic-mechanical complexes in solving specialized problems that require high dynamic characteristics.

Analysis of recent research and publications. Designs and control systems of robotic complexes are constantly being improved. Since the manipulator is driven by an electric drive, mechatronic control systems with feedback are widely used to improve its characteristics. The tasks of autonomous movement and manipulation of objects are successfully solved for various kinematic schemes, including anthropomorphic ones [2].

The most advanced are control systems that use elements of artificial intelligence, which are able to adapt to the parameters of the external and internal environment and recognize objects. Progressive solutions of artificial neural networks [3] make it possible to improve controllability and increase the level of autonomy of robotic complexes when moving over prepared areas and rough terrain.

Artificial intelligence allows capturing and manipulating objects of various configurations [4]. Developed neural networks also enable the robot to move independently on a complex surface and avoid obstacles.

The most common robotic complexes are those using electric drives controlled by a mechatronic system. As a rule, feedback sensors are used to obtain higher accuracy. However, the best result can be obtained by taking into account the ongoing work processes and the design of the mechanism elements.

Previously unsolved problems. Part of the previously unsolved problem is the study of the features of the mechanical system devices and the application of the obtained results as part of a detailed mathematical model, which is embedded in the form of a software module in the mechatronic control system. At the same time, the algorithms of robot engines and auxiliary devices will allow to ensure an increased level of accuracy of the system, which includes feedback sensors.

Therefore, it is necessary to develop a complex mathematical model that integrates blocks and modules that break the physical essence of system elements and take into account the peculiarities of their work.

The wide implementation of autonomous robotic complexes, in contrast to remotely controlled ones, requires solving a wider range of problems. The system must monitor and control the parameters of the actuators and the manipulator constantly. Depending on the readings of the sensors, drive control should be ensured according to complex adaptive laws. The type of object of manipulation determines the effort of grasping the object and its adjustment depending on external conditions. At the same time, the control system must find a balance between precise and fast movements.

One of the most important characteristics of a manipulator is accuracy. In the absence of the ability to provide it, the intelligent management system will not be able to perform the tasks. High accuracy in dynamics is quite difficult to ensure with the help of a control system that does not include a detailed mathematical model of the device, as well as in the absence of adjustable damping devices.

The purpose of research. The purpose of the work is a comprehensive study of the manipulator as part of the robotic complex. The latter includes the development of detailed mathematical models and determination of the dynamic characteristics of the mechanical system. Solving these tasks allows you to use adjustable damping devices in the complex, which allow you to obtain high dynamic characteristics and ensure the necessary accuracy when manipulating objects.

The tasks include the study of the schematic solution of the manipulator as part of the robotic complex, the determination of the loads on the deformations of its connections and the finding of dependencies describing the work processes, as well as the determination of the dynamic parameters of the system.

The obtained dependencies allow determining the combined effect of factors affecting positioning accuracy and dynamic characteristics of the manipulator. As a result of research, the task of developing a detailed dynamic model of a mechanical system is solved, which fully takes into account its working processes and allows you to use the advantages of using feedback sensors.

The use of adjustable damping devices as part of the manipulator allows you to solve the problem of obtaining the highest dynamic characteristics under the condition of studying the working processes of the dampers and integrating the obtained dependencies into the mechatronic control system.

Research results. Ground robotic complexes are equipped with a tracked chassis on which a lever-type manipulator is installed. In order to develop a dynamic mathematical model of the complex, preliminary experimental studies were conducted. During the experiments the robotic complex moved along a horizontal surface containing a rectangular protrusion. The movement of the mechanism elements was recorded visually with further processing of the received video files. At the same time, the geometric position of the connections of the manipulator and the chassis of the complex during its movement was determined.

Since dynamic loads of the manipulator took place during the movement, the smooth movements of the chassis are accompanied by small vibrations of the manipulator. When interacting with a rectangular protrusion, significant dynamic loads on the robotic complex occur. At the same time, intense oscillations of the manipulator are observed.

According to the results of the analysis of the vibrations displayed on the video recording, the concept of determining the dynamic characteristics of the ground robotic complex equipped with a lever manipulator is substantiated. The methodology includes considering the movements of the manipulator separately when it moves together with the chassis on a road surface containing an unevenness in the form of a rectangular protrusion. At the same time, the manipulator is considered to be non-deformed, and its position relative to the chassis is unchanged. The dynamic loads acting on the connections of the mechanical system are determined on the basis of the introduced assumption. At the same time, the dynamic deformations of the connections, which lead to small movements of the elements of the elastic system of the manipulator relative to the position of the chassis, are considered.

Based on the proposed concept, a method for determining the dynamic characteristics of a mobile ground robotic complex equipped with a lever-type manipulator has been developed. According to the algorithm, to determine the kinematic parameters of the mechanical system a dynamic model is applied in the form of a rigid body that performs plane movement, and the manipulator is considered to be fixed rigidly on the platform. The movements of the complex corresponding to the change in the positions of the manipulator connections are determined and found experimentally.

As a result of the measurements, the law of point A displacement and the dependence of angular displacements of the chassis were established: $z_A=z_A(t)$ and $\theta=\theta(t)$ (Fig. 1). The resulting regularities are input parameters for further mathematical modeling of the mechanical system.

When studying dynamic displacements, it is necessary to determine the deviation of the levers from their nominal position. These coordinate changes lead to displacements of hinges B and C of the manipulator (Fig. 1).

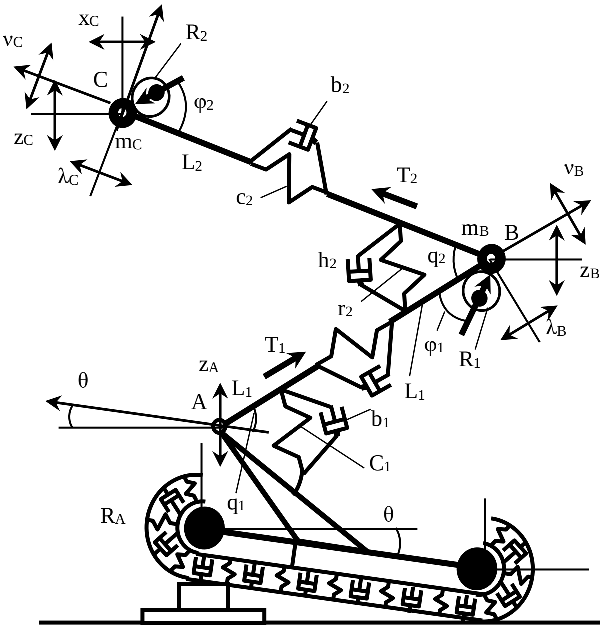
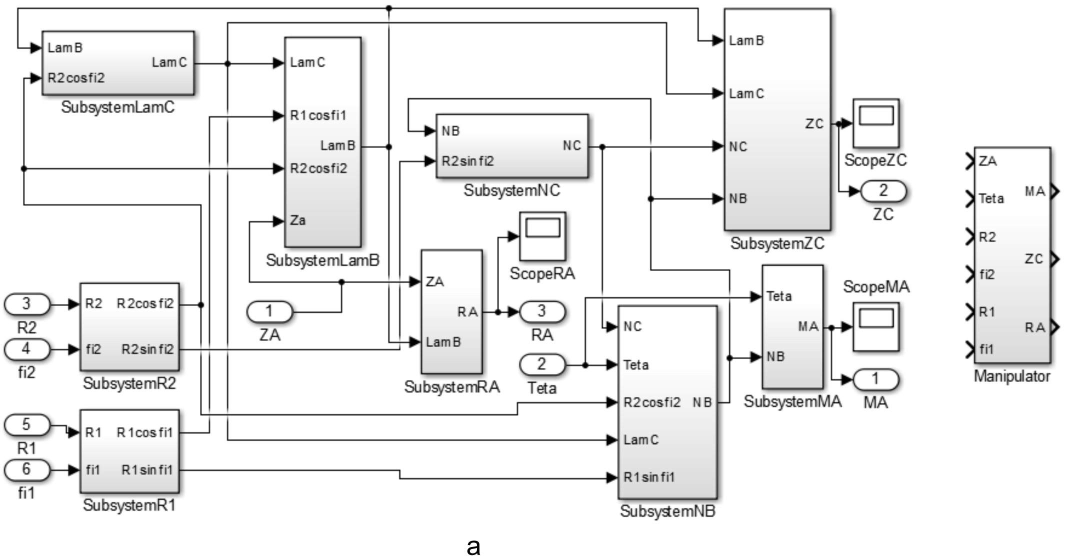


Fig. 1. Dynamic model of the manipulator

According to the proposed model, the dynamic movements of the manipulator connections occur due to the displacemnets of the chassis, which leads to vertical displacemnet z_A of hinge A and its transverse angular movements by an angle θ. The manipulator is presented in the form of two masses m_B and m_C, which are concentrated in the hinges B and C. The levers of the manipulator are assumed to be deformed, and the rotary assemblies with the corresponding stiffnesses and resistance coefficients. The model takes into account the presence of controlled dampers that are part of the rotary assemblies. These devices dampen oscillations by creating pulsed dynamic loads R_1 and R_2 oriented at angles $\varphi1$, $\varphi2$ to the lever axes.

Based on the proposed dynamic scheme, a mathematical model was developed that describes the physical processes taking place in the manipulator of the ground robotic complex equipped with controlled damping devices [5].

Separate blocks correspond to the elements of the mechanical system of the manipulator and reveal the nature of mechanical processes in connections, rotary assemblies and damping devices. The elements of the model are interconnected, which allows monitoring the dynamic parameters of the mechanism and influencing them with the help of adjustable dampers. The mathematical model is implemented in the Simulink environment of the MATLAB package in the form of an integral structural model of the manipulator (Fig. 2).



a

Fig. 2. The general structure of the mathematical model of the manipulator (a) and the presentation of this model in the form of one block (b)

The Subsystem R_1 and Subsystem R_2 blocks are introduced into the model, which allow you to calculate the projections of the forces of each damper on the axis of the lever and perpendicular to its axis.

The obtained mathematical dependencies and algorithms are implemented in the form of a software module that can be directly used as part of the mechatronic control system of a robotic complex without making changes to its mechanical system. Modernization will be required only at the software level.

To match the system of dynamic damping of vibration oscillations with the developed integral model of the manipulator during the movement of the robotic complex on complex terrain, one should take into account the effectiveness of vibration damping when external and internal operating conditions change, which affect directly the amplitudes of the vertical acceleration of the supporting part (the spring-loaded part of the manipulator) and the chassis (which is not spring-loaded) [6, 7, 8]. The smaller this value, the higher the stability and the lower the displacements of the manipulator levers relative to their nominal position as part of a moving dynamic system.

To evaluate the effectiveness of the manipulator's dynamic system, we can apply the load on the suspension unit, which is necessary for any horizontal power transmission. Let's determine the effective (effective) value of the load fluctuations on the crawler chassis:

$$F_{z\,ef} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(F_{z,i} - F_{z,ref}\right)^2}. \qquad (1)$$

At the same time, n corresponds to the number of considered measured values. To calculate the effective value in dependence (1), the static load on the tracked chassis $F_{z,stat}$ and the basic (reference) $F_{z,ref}$ value are used. This makes sense in cases where dynamic properties are determined in one-dimensional space (only vertical displacements are considered). The two-mass oscillator shown in Fig.3 is often used as a model for research.

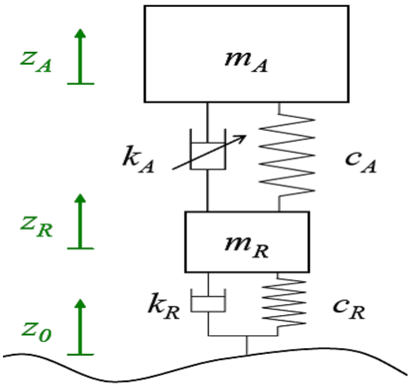


Fig. 3. Model of a two-mass dynamic system

The conducted studies [9] showed that the elastic and viscous properties of shock absorbers can be modeled very well using the Maxwell field. The model includes a spring and a nonlinear shock absorber connected in series (index s), and an additional spring is used, placed parallel to the introduced dynamic connection (index p) (Fig. 4).

It is possible to represent the global coordinate with the help of a simplified model that determines the position of the connection as:

$$X = X_p = X_{ds} + X_{cs}, \qquad (2)$$

and the relative velocity as:

$$X = X_p = X_{ds} + X_{cs}. \qquad (3)$$

The global damping force is the sum of the forces of parallel and serial dynamic connections

$$F = F_p + F_s. \qquad (4)$$

The force in the parallel part is determined by linear elasticity and prestressing forces:

$$F = F_o + c_{px}. \qquad (5)$$

The force in the series circuit can be found for the spring

$$F_s = c_s \cdot x_{cs}, \qquad (6)$$

as well as in the case of a non-linear depreciation characteristic

$$F_s = F_s(x_{ds}). \qquad (7)$$

Dependence (7) is based on the hydraulic model of the device and is intended to describe nonlinear characteristics during damping. The linear mechanical stiffness of series and parallel springs is denoted as C_s and C_p , respectively.

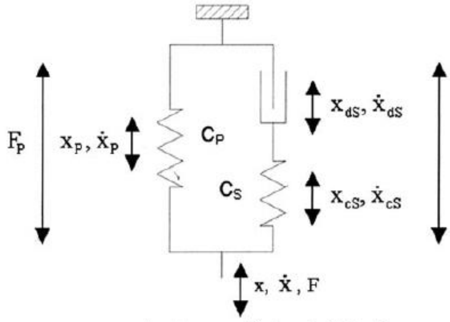


Fig. 4. Rheological model of a single-cylinder shock absorber

The nonlinear damping characteristic for the global relative speed is inverted:

$$X_{ds} = \Phi(F_5) = \Phi\left(F - C_{px} - F_o\right). \qquad (8)$$

It is used in combination with derived formulas:

$$C_s X_{cs} = F - C_{px}, \qquad (9)$$

$$\dot{x} = \Phi(F_s)\frac{C_s}{C_s+C_p} + \frac{1}{C_s+C_p} = \dot{F} = \Phi_F + \delta\dot{F}, \qquad (10)$$

$$F_s = \Phi(F_s)\frac{C_s}{C_s+C_p}. \qquad (11)$$

At the same time, the elasticity is determined according to the dependence:

$$\delta = \frac{1}{C_s+C_p}. \qquad (12)$$

The basis for creating a mathematical model of the system of dynamic damping of vibration oscillations of the manipulator is the differential equations that describe the processes in the complex oscillatory circuit shown in Fig. 1.

The mathematical model describing the oscillations of the studied system is represented by the dependence:

$$\frac{d}{dt}\left(\frac{dT}{dq_i}\right)-\frac{dT}{dq_i}+\frac{d\Pi}{dq_i}+\frac{d\Phi}{dq_i}=\sum Q_i, \quad (13)$$

where qi – is a generalized coordinate; T – kinetic energy; П – potential energy; Ф – is Rayleigh's dissipative function; Qi is an external disturbance.

Hydraulic dampers allow you to ensure the specified speed of the mechanism convictions and absorb part of the kinetic energy in order to reduce oscillations [8, 10]. However, during long-term operation of the dampers, the temperature of the working fluids increases significantly due to energy absorption and viscous friction in the throttle elements. This leads to a decrease in the viscosity and rheological characteristics of liquids, which in turn negatively affects the stability of the damper devices. However, the use of magnetorheological fluid (MRF) in the damper allows to solve the problem of stabilizing the flow characteristics of the damper.

The advantage is the possibility of high-precision control of the viscosity and other mechanical properties of the liquid under the influence of a magnetic field applied to it. This allows you to control hydrodynamic processes according to the given laws and sensor data using a microcontroller. In this case, control is carried out through external magnetic fields. This method allows you to regulate the flow of the working fluid precisely and it is the most rational in comparison with other options when used as part of the suspension unit. The damper is able to work in a wide temperature range and has small geometric dimensions.

It is most rational to control the resistance force of the damper using a magnetic field applied to a magneto-rheological fluid, which includes particles the size of which is 0.00001 mm. The viscosity of the ferromagnetic liquid can be changed dozens of times, and the response time does not exceed 40 ms [9]. An important advantage of the considered liquid is the possibility of its use at temperatures reaching –30°C. Magnetic particles are covered with surface-active substances which prevents them from sticking together. The schematic diagram of a damper using a magneto-rheological fluid and an alternating magnetic field is shown in Fig. 5. An electromagnet is built into the piston of the damper, and the controller supervises the power of the current due to electric impulses supplied to the coil. A magnetic field is created on it, due to which magnetic particles are activated in chains, which leads to an increase in the viscosity of the MRR in the throttle. The cylinder cavities are filled with MRP, and the cylinder and piston are made of magnetic material. When the piston moves, the liquid flows from one cavity to another through a narrow annular gap. Since the hydraulic resistance of the gap determines the magnitude of the damping force F and the speed of the piston, the control of the damper is reduced to changing the hydraulic resistance by creating a radial magnetic field of a given intensity in the gap, which occurs as a result of passing the control current through the excitation coil.

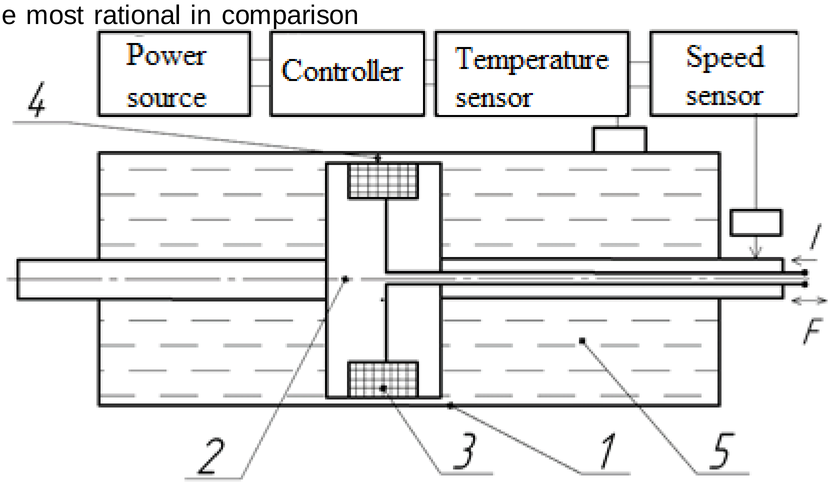


Fig. 5. Damper using a magneto-rheological fluid and an alternating magnetic field (1- cylinder; 2- piston with a rod; 3- excitation winding; 4- throttle concentric channel; 5- magneto-rheological fluid)

Kinematic viscosity is the main indicator for all liquids used in dampers, and on which the resistance force significantly depends [7]:

$$\nu=\frac{dP_\tau}{ds\cdot\left|\frac{du}{dz}\right|\cdot\rho}, \quad (14)$$

where dP_τ- force of viscous friction, ds - the contact area of the layers in the liquid part; $\left|\frac{du}{dz}\right|$- velocity gradient module; du - velocity difference on fluid shear planes; dz - the distance between the planes.

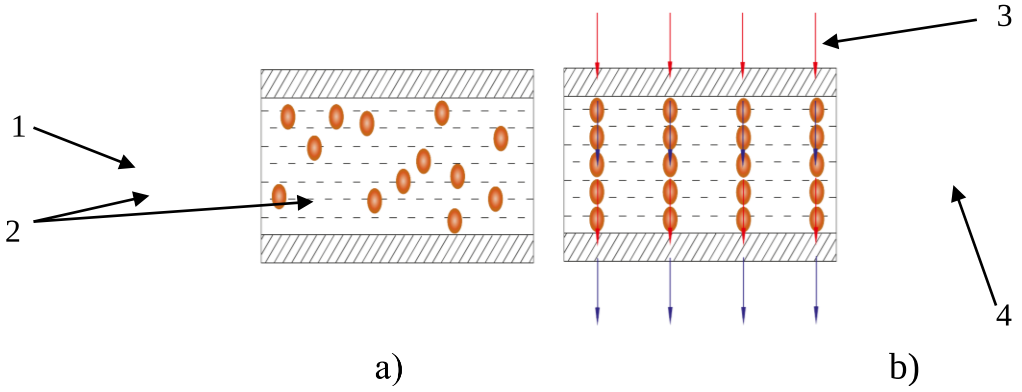
The resistance force on the damper rod during "compression" is F_c, and during "return" - F_v. Taking into account the variable properties of the MRP and geometric parameters, the forces acting on the piston can be represented by the following expressions:

$$F_c = p \times F_b = \frac{Q^2\rho}{2\mu F_p} F_b, \tag{15}$$

$$F_v = \frac{Q^2\rho}{0.1F_g\sqrt{\frac{\vartheta_d}{\frac{\tau_0 e^{kh}}{V}+\nu}}} F_b, \tag{16}$$

where Q is the fluid flow through the throttle, F_b is the area of the piston, V is the speed of the piston, ρ is the density of the working fluid, τ_0 is the yield strength of the MPR, k is the curvature coefficient of the dependence $\tau_0 = f(H)$; H - magnetic field strength, ϑ_d - fluid flow rate, F_g - area of the piston bore, p - pressure of the working fluid during "compression" and "return".

Two states are distinguished for a magnetorheological fluid: activated and non-activated. During throttling of an activated magnetorheological fluid with a constant drag force, the flow rate will decrease. Due to the magnetorheological effect, it is possible to directly increase the viscosity of the magnetorheological fluid (Fig. 6) and control the damper characteristics.



(a – no magnetic field, b – under the influence of a magnetic field): 1- carrier liquid; 2- magnetic particles; 3- direction of magnetic field lines; 4- a circuit formed by magnetic particles

Fig. 6. Scheme of activation of ferromagnetic liquid

This liquid is Newtonian in the unactivated state, and therefore, in the general case, the flow of liquid through the annular gap of the throttle is described by the Poiseuille formula for calculating pipelines with a laminar regime [8, 9] and the Newtonian component of the pressure drop ΔP_τ is a function that depends on the fluid stress of the suspension and geometric gap parameters:

$$\Delta P_\eta = f(\tau_y, L, h) \tag{17}$$

In a general form the dependence for a throttle with an annular working gap, in which shear stresses act, and the liquid is activated, can be written as:

$$\Delta P_\tau = \frac{c\tau_H(H)L}{h} \tag{18}$$

where *c* - coefficient depending on the ratio *ΔP_τ / ΔP_η* (according to the work data [4] *c = 2* for *ΔP_τ / ΔP_η <<1* and *c = 3* for *ΔP_τ / ΔP_η > 100*).

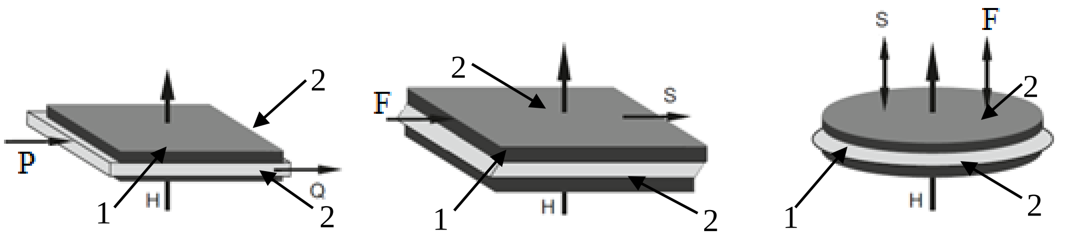
Using dependence (18), we can propose general formulas for determining the pressure drop in the magnetorheological damper:

$$\Delta P_{vis} = \Delta P_\eta = \frac{12\rho\nu QL}{\pi B(r_2-r_1)^3}, \tag{19}$$

$$\Delta P_{mr} = \Delta P_\tau + \Delta P_{vis} = \frac{c\tau_y L}{r_2-r_1} + \Delta P_{vis}, \tag{20}$$

where ΔP_{vis} – pressure drop for non-activated liquid, ΔP_{mr} – pressure drop for activated liquid, B – damper circle length, r_2 – damper cylinder radius, r_1 – piston radius, r_2-r_1 – width of concentric gap, L – length of concentric gap (piston), τ_y is the yield strength of the structured medium.

The following characteristic modes of magnetorheological fluid operation are distinguished (Fig. 7): valve mode, shear mode, compression mode.



valve mode shear mode compression mode

Fig. 7. Characteristic modes of operation of a ferromagnetic liquid (1- ferromagnetic liquid; 2-fixed plates)

The main characteristic that describes the operation process of the magnetorheological damper is the dependence of the flow rate of the magnetorheological fluid on the intensity of the applied magnetic field. As a result of the research [8, 9], a dependence was obtained (Fig. 8).

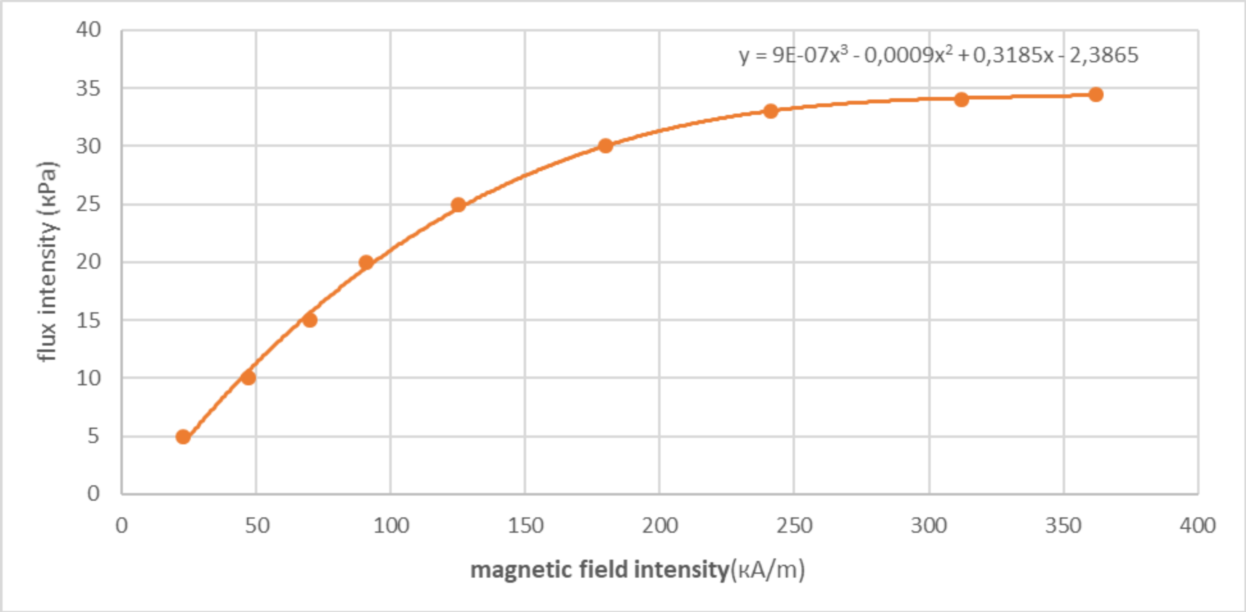


Fig. 8. Dependence of flux intensity on magnetic field intensity

Using this regularity, it is possible to calculate the necessary geometric parameters of the magnetorheological damper and its throttle calibrated concentric channel (Fig. 8). It follows from the dependence of the yield stress on the strength of the magnetic field that a supersaturation effect is observed in magnetic fluids. After reaching a certain value of the magnitude of the magnetic field, the yield stress remains practically constant, and further growth of the magnetic field does not affect the rheological characteristics of the liquid significantly. It is advisable to set the magnetic field strength to 200 kA/m for the studied magnetorheological fluid.

Conclusions. The proposed mathematical model of the robotic complex manipulator, when applied as part of the mechatronic control system, allows to improve significantly the accuracy and dynamic characteristics of the mechanism. The software module, developed on its basis, can be integrated into the existing robotic complex without making changes to its design and electronic part.

Based on the analysis of the working processes of the elements of the mechanical system, detailed modules and mathematical models have been developed, which make it possible to increase the technical level of the manipulators and to use the advantages of the existing control system in full.

An adjustable damper, that uses a magnetorheological fluid to control the operating characteristic, is investigated in the paper. A method, that can be used to calculate a magnetorheological damper, has been developed. The results show the potential of the proposed method of controlling the damper characteristics by changing the properties of the magnetorheological fluid. It has been established that controlled damping devices are optimal for such mechanical systems and will provide for effective damping of oscillations with adjustable damping coefficients.

The advantage of the design of the damper studied in the research is the ability to control the characteristics of the device directly using electrical signals that do not require additional converters. However, to ensure the functioning of the vibration damping system, high accuracy and the ability to change the characteristic quickly are required.

References

1. Maarten de Waard & Maarten Inja & Arnoud Visser (2013) Analysis of flat terrain for the atlas robot. *2013 3rd Joint Conference of AI & Robotics and 5th RoboCup Iran Open International Symposium*, 1-6. DOI: 10.1109/RIOS.2013.6595324.
2. Sangbae Kim & Patrick Wensing (2017). Design of Dynamic Legged Robots *Foundations and Trends in Robotics 5(2)*, 117-190. DOI:10.1561/2300000044.
3. Sorin Grigorescu & Bogdan Trasnea & Tiberiu Cocias & Gigel Macesanu (2019) A Survey of Deep Learning Techniques for Autonomous Driving. *J Field Robotics 37*, 362– 386. DOI:10.1002/rob.21918.
4. D. Dholakiya et al. (2019). Design, Development and Experimental Realization of a Quadrupedal Research Platform: Stoch, *2019 5th International Conference on Control, Automation and Robotics (ICCAR)*, 229-234. DOI: 10.1109/ICCAR.2019.8813480.
5. Strutynskyi S.V. (2019) Determination method of dynamic characteristics of mobile terrestrial robotic complex manipulator*. IOP Conf. Ser.: Mater. Sci. Eng. 708 012031*. DOI 10.1088/1757-899X/708/1/012031.
6. Shulman Z.P. (1982) Magnitoreologicheskiy effekt [Magnetorheological effect]. Mn.: Nauka i tekhnika [in Russian].
7. Mikhailov V.P. & Stepanov G.V. & Bazinenkov A.M. et al. (2010) Magnitoreologicheskiye ustroystva aktivnoy vibroizolyatsii i pozitsionirovaniya dlya nanotekhnologicheskogo oborudovaniya [Magnetorheological devices for active vibration isolation and positioning for nanotechnological equipment]. *Vestnik MGTU im. N.E. Bauman, series "Instrument making", special issue “Nanoengineering”*, 138-148 [in Russian].
8. Seok-Jun Moon & Chae-Wook Lim & Byung-Hyun Kim & Young-Jim Park (2005) Vibration control of a beam using linear magnetostrictive actuators. *Smart Structures and Materials: Damping and Isolation. Proceedings of SPIE Vol. 5760*.
9. Kostyuk, I.V. & Nochnichenko, I.V. (2016) Do pytannya pobudovy dempfera protezu nohy na osnovi mahnitoreolohichnoyi ridyny [On the question of building a damper for a leg prosthesis based on a magnetorheological fluid]. *International scientific and technical conference “Hydraulic and pneumatic drives of machines - modern achievements and applications”*, 58 - 60 [in Ukrainian].
10. Galetskii O.S. & Nochnichenko I.V. (2014) Zastosuvannya yavyshcha perenosu ta informatsiynoyi entropiyi do analizu povedinky mahnitoreolohichnoho dempfera [Experimental study of magnetorheological choke]. *XV international scientific and technical conference “Progressive technique, technology and engineering education”,* 30-32 [in Ukrainian].

ЗАСТОСУВАННЯ РЕГУЛЬОВАНИХ ДЕМПФЕРНИХ ПРИСТРОЇВ ДЛЯ ПІДВИЩЕННЯ ТЕХНІЧНОГО РІВНЯ НАЗЕМНИХ РОБОТИЗОВАНИХ КОМПЛЕКСІВ, ОСНАЩЕНИХ МАНІПУЛЯТОРОМ

Розроблена динамічна модель маніпулятора роботизованого комплексу, що базується на основі проведених експериментальних досліджень. По результатам аналізу коливань запропоновано концепцію визначення динамічних характеристик механічної системи. Алгоритм доповнено модулями, які враховують можливість застосування керованих демпферних пристроїв.

Складові частини моделі представляють механічні пристрої маніпулятора, зокрема ланки, поворотні вузли та демпферні пристрої. Модель містить усі зв’язки між модулями, що дозволяє дослідити динамічні параметри у процесі роботи механізму. Для реалізації математичної моделі, що включає підсистему динамічного гасіння вібраційних коливань маніпулятора запропоновані диференціальні залежності, що у повній мірі розкривають суть коливальних процесів механічної системи. Керовані демпферні пристрої, що введені у модель дозволяють здійснювати управління параметрами з метою підвищення точності механізму.

Математична модель реалізована у вигляді програмного модуля, що враховує впливові робочі процеси які протікають у ланках та поворотних вузлах механічної системи роботизованого комплексу.

Алгоритм передбачає застосування мехатронної системи, що обладнана датчиками зворотного зв’язку для управління маніпулятором. Керовані демпферні пристрої

дозволяють підвищити технічний рівень та покращити динамічні характеристики механічної системи. У роботі досліджено гасіння коливань мехатронною системою зі зворотніми зв'язками та визначено вплив від гасіння коливань на параметри точності при переміщенні роботизованого комплексу по нерівній поверхні.

У роботі представлені результати моделювання регульованого демпфера у складі рухомої механічної системи. Інноваційний пристрій використовує магнітореологічну рідину у якості робочої, що дозволяє керувати ним за допомогою електричних імпульсів. Проведені експериментальні дослідження дозволили отримати ключові показники та його робочу характеристикою демпферу. На основі даних результатів запропоновані залежності. що визначають закони керування демпфером, який використовує магнітореологічну рідину.

Ключові слова: наземний роботизований комплекс, маніпулятор, мехатронна система, математичне моделювання, динамічні характеристики, демпфер, точність.

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