Force control optimization in force compensation systems with elastic mechanical gears

Georgy Yakovlevich Pyatibratov, Oleg Aleksandrovich Kravchenko, Nikolay Aleksandrovich Sukhenko

Federal State Budget Educational Institution of Higher Professional Education, Platov South-Russian State
Polytechnic University (NPI), Prosveshcheniya Street, 132, Novocherkassk, 346428, Russia

Abstract. For a determination of limits in a provision of required quality of force control in the discussed electromechanical force compensation systems (FCS), it is proposed to perform synthesis of control devices in optimal statement with an implementation of a linearized model. The objective of the presented study is a solution, in optimal statement, of a problem of a force regulator's synthesis in FCS, which comprises elastic mechanical gears, significant force of friction and inertia, which are additionally attached to weight relieved object of masses. It is reasonable to solve problems of synthesis of forces' optimal control in gears' elastic elements in FCS, which compensate force of gravity of weight relieved object, using methods of classical variations calculus. An application of integral criterion of forces' control quality will allow to determine a rational structure and synthesize optimal parameters' values a force regulator, during an operation of FCS in a context of uncertain perturbation actions. Performed theoretical and experimental studies demonstrated effectiveness of the synthesized force regulator in FCS in a case of changes in uniform perturbation actions. The synthesized force regulator allows reduce static error of force control in 36.5 times, and overcontrol of force in elastic mechanical gear - in 5.5 times as compared with the initial mechanical system without an electric drive. The proposed method for a synthesis of optimal force regulator in FCS was tested during a creation of training simulator "Exit 2", which was designed to train astronauts in a spacesuit with total weight of 250 kg for a work in a condition of zero gravity, and during a creation of balanced type manipulators MP100 with 100 kg load-carrying capability.

[Pyatibratov G.Y., Kravchenko O.A., Sukhenko N.A. **Force control optimization in force compensation systems with elastic mechanical gears.** *Life Sci J* 2014;11(12):178-184] (ISSN:1097-8135). http://www.lifesciencesite.com. 30

Keywords: synthesis, optimization, variational methods, elasticity, forces, electric drive

Introduction

Problems of an improvement of testbed facilities for trying-out of space technology [1], training simulators [2], modern manipulators and robotics systems [3] led to an emerge and an intensive development of a new class of electromechanical force compensation systems (FCS) [4]. The main requirement for a practical implementation of FCS is a high-precision compensation of components of forces using an electric drive (ED), caused by gravity of moved objects, forces of friction of mechanisms and elasticity of mechanical gears, as well as force of inertia of additionally attached masses and actuating units. Features of an implementation and an operation of discussed systems are determined by an availability of elastic mechanical gears, as well as significant forces of friction and inertia, masses, which are additionally attached to an object [5]. For a determination of limits in a provision of required quality of forces' control in the discussed FCS, it is proposed to perform synthesis of control devices in optimal statement with an implementation of a linearized model of electromechanical systems (EMS) with elastic linkage (EL). Analysis of nowadays approaches to synthesis of automated systems, produced with an implementation of the maximum principle of L.S. Pontryagin [6], analytical design of optimal regulators [7], adaptive methods [8], neural networks [9] and fuzzy logic [10] showed that synthesis of FCS with variations calculus' methods implementation [11].

Methodology

A mathematical description of a linearized dual mass electrochemical system, which regulates forces in elastic elements (EE) of mechanical gear, obtained in [12, 13], is presented in fig.1 in a form of flow chart. In the flow chart coordinates of the systems have the following notations: Ω_D, Ω_M – speeds of the drive and the object; M_0 – constant component of moment generated by gravity of the object; M_{Ea} – moment, proportional to a value of changing external force, applied to the object of control; M_D and M_{el} – moments of the drive and EE; U_{AC} – signal of the drive's current specification, which is proportional to moment M_0; U_{FF} – feedback signal by force. In the presented mathematical model EMS with EL moment M_{el} and speed Ω_M must be set to a drive's shaft.

Parameters: k_{Em} , T_{Em} – coefficient of transfer and the electromagnetic constant of a drive's time; T_D, T_M – mechanical constants of time of inertial masses of a drive and an object, separated by EE; T_C , T_d – constants of time, considering equivalent rigidity and dissipative properties of mechanical gears; k_{SC} , k_E – coefficients of transfer of feedback through current and feedback, through counter electromotive force of a drive, which characterize properties of a fixed part of a system.

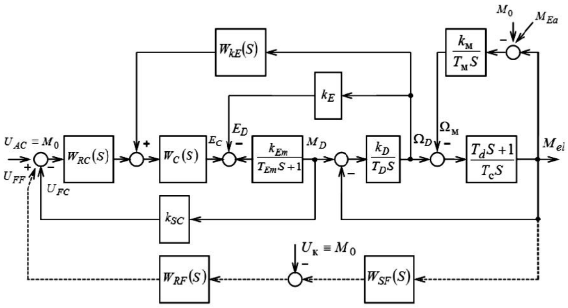

Fig.1. Flow chart of the studied FCS

Transfer functions $W_{kE}(S)$, $W_{SF}(S)$, $W_C(S)$, $W_{RC}(S)$, $W_{RF}(S)$ describe dynamic properties of a compensation channel of counter electromotive force of a drive, force sensor, voltage converters, which supplies a drive, current regulators of a drive's current and force in EE. In order to summarize the results, a mathematical description of the studied EMS with EL is obtained, with an implementation in relative units: Speeds Ω_D and Ω_M are defined as a fraction of a drive's idle speeds Ω_0; EMF of a converter E_C and a drive E_D – from nominal voltage of a drive, and moments M_D , M_{el} , M_0 and M_{Ea} – from nominal moment of a drive M_R . With a selected basic coordinates' values of EMS with EL, mechanism parameters must be determined using the following equations: $T_D = J_D \Omega_0 M_R^{-1}$; $T_M = J_M \Omega_0 M_R^{-1}$; $T_c = c_{el}^{-1} \Omega_0 M_R^{-1}$; $T_d = b_{el} c_{el}^{-1}$, where J_D and J_M – moments of inertia of a drive and an object; c_{el} и b_{el} - coefficients, taking into account equivalent rigidity and internal viscous friction of EE of mechanical gears. Basic values of assigning voltage U_{ACb} and at current sensor's output U_{FCb} were selected in the manner that makes static transfer coefficient of feedback's circuit by current equal to one. An implementation of relative units allowed to simplify mathematical description of the studied system and allowed to obtain $k_E = k_{SC} = k_D = k_M = 1$.

In the studied FCS a force assignment, in accordance with the requirements of its operation, must be permanent $U_{AC} = \text{const}$ and be equal to M_0, so transition processes for perturbation actions could be investigated as a change of increments in EE. In that case, the aim of forces control of FCS is a minimization of moment's deviation in EE M_{el} , caused by a change in an external perturbation M_{Ea} .

In order to provide for the high demands of quality of forces control in FCS, force regulator $W_{RF}(S)$ must be synthesized using optimal control. During synthesis of optimal force regulator (OFR) it is desirable to take into account real limitations, which is put on control action, and to guarantee stability of a control system with a synthesized force regulator to possible changes of parameters of an object of control [14].

Synthesis of OFR conducting for EMS with EL described by the mathematical model, presented in fig. 1. The equation, which describes a change of moment M_{el} in EL of FCS mechanism, can be presented in the following form:

$$M_{el}(S) = [U_{AC}(S) + U_{FF}(S)] W_{FCa}(S) + [M_0(S) + M_{Ea}(S)] W_{FPa}(S) , \qquad (1)$$

where $U_{FF}(S) = W_{SF}(S) W_{RF}(S) M_{el}(S)$ - a control action, which ensures the required quality of forces' control in EE.

During synthesis of OFR making following assumptions: EMF of a drive is fully compensated by a channel with transfer function $W_{kE}(S) = \dfrac{k_E}{W_C(S)}$; properties of closed circuit of current are considered by aperiodic link of first order with the transfer function

$W_{CC}(S)=\dfrac{k_{CC}}{T_{CC}S+1}$; channel of force measurement in early stages study is accepted to be inertialess $W_{SF}(S)=k_{SF}$. With the condition $M_0=\text{const}$, a change in EE M_{el} , considering synthesized OFR in a case of an action of moment M_{Ea} , can be determined by solving of the equation

$$M_{el}(S)=U_{FF}(S)W_{FPa}(S)+M_{Ea}(S)W_{FPa}(S), \qquad (2)$$

where $W_{FCa}(S)$, $W_{FPa}(S)$ – transfer functions of open circuit system for control and perturbation actions. Taking into account the parameters that characterize generalized properties of a mechanical part of the system $\gamma=\dfrac{T_D+T_M}{T_D}=\dfrac{J_D+J_M}{J_D}$;

$\beta=\dfrac{T_M}{T_D\gamma}=\dfrac{J_M}{J_D\gamma}$;

$T_{el}=\dfrac{T_D T_M T_c}{T_D+T_M}=\dfrac{1}{\gamma}\dfrac{J_M}{c_{el}}$,discussed functions can be presented in the following form

$$W_{FCa}(S)=\frac{M_{el}(S)}{U_{AC}(S)}=\frac{\beta k_{CC}(T_d S+1)}{\left(T_{el}^2 S^2+T_d S+1\right)\left(T_{CC}S+1\right)}; \qquad (3)$$

$$W_{FPa}(S)=\frac{M_{el}(S)}{M_0(S)+M_{Ea}(S)}=\frac{1}{\gamma}\frac{T_d S+1}{T_{el}^2 S^2+T_d S+1} \qquad (4)$$

Substituting in the expression (1) transfer functions (3) and (4), obtaining the equation, which allows, in a context of a selected criteria of optimality and energy restrictions of ED, to find the required control U_{FF} :

$$A(S)M_{el}(S)=B(S)U_{FF}(S)+C(S)M_{Ea}(S), \qquad (5)$$

where $A(S)=a_3S^3+a_2S^2+a_1S+a_0$ – polynomial, which takes into account the general properties of the studied system; $B(S)=b_1S+b_0$ – polynomial during a control action; $C(S)=c_2S^2+c_1S+c_0$ – polynomial during a perturbation action; $a_3=T_{el}^2T_{CC}$; $a_2=T_{el}^2+T_dT_{CC}$; $a_1=T_d+T_{CC}$; $a_0=1$; $b_1=\beta k_{CC}T_d$; $b_0=\beta k_{CC}$; $c_2=(T_dT_{CC})/\gamma$; $c_1=(T_d+T_{CC})/\gamma$; $c_0=1/\gamma$.

An analysis of requirements to FCS of testbeds [1], training simulators [2], balanced manipulators [3] showed that, in a context of requirements and features of their operation during synthesis OFR it is necessary to minimize average square (dispersion) of moment's deviation in EE during an operation of the system t_f . In a practice an actual time t_f is many times larger than the largest time constant of FCS, therefore, criteria for quality of control of EMS with EL can be presented in a form of functional $J_1=\lim\limits_{t_f\to\infty}\dfrac{1}{t_f}\int_0^{t_f}M_{el}^2(t)dt$. At the same time, acceptable values of maximum moment of an electric drive $M_{D\max}$ or current supplying its converter $I_{C\max}$ can be taken into account in a form of a restriction on module of control action $|U_{FF}|\le U_{\max}$. However, that approach makes FCS optimal control problem non-linear [15]. For synthesis of OFR in linear setting it is proposed take into account limitations on a power of an electric drive (ED), using an average square of control action in the form of $U_{FF}^2=\dfrac{U_{\max}^2}{k_U^2}$, where k_U – coefficient that determines time during which optimal control U_{FF} might have restrictions. The obtained limit on permissible power of ED, in accordance with rules of solutions of variations calculus's isoperimetric problems, it is reasonable to determine by means of supplementing functional J_1 component, which consider a power of control actions U_{FF} , multiplied by a Lagrangian multiplier [lambda]: $J_2=\lim\limits_{t_f\to\infty}\dfrac{1}{t_f}\int_0^{t_f}\left(M_{el}^2+\lambda U_{FF}^2\right)dt$. Variables in functional J_2 can be reduces to one dimensionality using coefficient of a relationship between an output coordinate M_{el} and a control action U_{FF} ,which can be determined during an operation of EMS with

EL in a steady regime: $M_{el} = \frac{T_M}{T_D + T_M} k_{CC} U_{FF} = \beta k_{CC} U_{FF}$.

After normalization of variables, functional J_2 that was reduced to dimensionality of a regulated coordinate, can be presented in the following form:

$$J_3 = \lim_{t_f \to \infty} \frac{1}{t_f} \int_0^{t_f} \left[M_{el}^2 + \lambda (\beta k_{CC})^2 U_{FF}^2 \right] dt .$$

According to Legendre condition, minimum of that functional will be at values $\lambda \geq 0$, therefore, if it is specified as $\lambda (\beta k_{CC})^2 = 1/m^2$, the found functional will have more convenient form for a solution of the problem:

$$J_3 = \lim_{t_f \to \infty} \frac{1}{t_f} \int_0^{t_f} \left(m^2 M_{el}^2 + U_{FF}^2 \right) dt . \qquad (6)$$

On the basis of the obtained expression the problem of optimal force control in EE of a mechanism can be formulated as follows: in EMS with EL it is required to determine transfer function of force regulator $W_{RF}(S)$, which will provide minimum for the functional (6).

In the work [15] it is showed, that by arranging obtained form the equation (5) expression[$A(S)a(S) + B(S)b(S)$]in a form of polynomial, which has poles only in left half plane, transfer function of OFR can be obtained in the following form:

$$W_{RF}(S) = k_{RF} \frac{(T_1 S + 1)(T_{CC} S + 1)}{(T_2 S + 1)(T_d S + 1)}, \qquad (7)$$

where $k_{RF} = \frac{T_{CC} T_d + g T_{el}^2 T_{CC} + T_{el}^2 \sqrt{1 + m_1^2}}{\beta k_{CC} k_{SF} T_{CC} \left(T_d + g T_{el}^2 \right)}$;

$$T_1 = \frac{\left(2 g T_{el}^2 T_d + 3 T_d^2 + g^2 T_{el}^4 \right) T_{CC}^2 - T_{el}^4}{2 T_{CC} \left(T_{CC} T_d + g T_{el}^2 T_{CC} + T_{el}^2 \sqrt{1 + m_1^2} \right)}; \; T_2 = -\frac{T_{el}^2}{T_d + g T_{el}^2};$$

$$m_1^2 = \frac{1}{\lambda} = m^2 (\beta K_{SF} K_{TCC}); \; g = -\left| x_1 + 2 \operatorname{Re}(x_{2,3}) \right|;$$

$$x_1 = -\sqrt{D + L - \frac{z_4}{3}} x_{2,3} = -\sqrt{-\frac{D + L}{2} - \frac{z_4}{3} \pm j \frac{\sqrt{3}}{2} (D - L)}; \; D = \sqrt[3]{-\frac{u}{2} + \sqrt{v}};$$

$$L = \sqrt[3]{-\frac{u}{2} - \sqrt{v}}; \; u = 2 \left(\frac{z_4}{3} \right)^3 - \frac{z_4 z_2}{3} + z_0; \; v = \left(\frac{p}{3} \right)^3 + \left(\frac{u}{2} \right)^2; \; p = -\frac{z_4^2}{3} + z_2;$$

$$z_4 = \frac{2 T_{el}^2 T_{CC}^2 - T_{el}^4 T - T_d^2 T_{CC}^2}{T_{el}^4 T_{CC}^2}; \; z_2 = \frac{T_d^2 + T_{CC}^2 + m_1^2 T_d^2 - 2 T_{el}^2}{T_{el}^4 T_{CC}^2}; \; z_0 = -\frac{1 + m_1^2}{T_{el}^4 T_{CC}^2}.$$

In order to determine the parameters of OFR in transfer function (7), it is necessary to know the value of coefficient m_1, which provides the required minimum of functional (6), characterizing parameters of EMS with EL. At that, acceptable values of maximum moment of an electric drive and a converter's current are necessary to be determined in accordance with the methodology described in [16]. After an obtainment of m_1 parameters of synthesis of optimal regulator, ensuring required forces' control in FCS, k_{RF}, T_1 and T_2 can be determined.

Results

Analyzing effectiveness of synthesized OFC in EMS with EL, which has the following parameters of an invariable part: $T_D = 0{,}174$ s; $T_M = 0{,}032$ s; $T_c = 0{,}084$ s; $T_d = 0{,}0015$ s; $T_{CC} = 0{,}002$ s; $k_{CC} = 1$; $k_{SF} = 3{,}8$, which, in a case of basic values, $M_A = M_R = 10{,}37$ N·м, $\Omega_B = \Omega_0 = 139$ rad/s, $U_{ACb} = 0{,}4$ V are determining following values of generalized parameters: $\gamma = 1{,}184$; $\beta = 0{,}155$; $T_{el} = 0{,}048$ s.

With a value of coefficient $m_1 = 45$ transfer function of OFC has the following form:

$$W_{RF}(S) = -53{,}2 \frac{(0{,}012 S + 1)(0{,}002 S + 1)}{(0{,}0014 S + 1)(0{,}0015 S + 1)}$$

.

Minus sign of the coefficient of obtained transfer function's strengthening, indicates a necessity of an introduction in the system of negative feedback by a force.

The study of transition processes in FCS allow to determine efficiency of the proposed methodology of synthesis of OFC in EMS with EL. In the fig. 2 transition processes in the studied FCS are presented, which were obtained during a perturbation action $M_{Ea} = 0{,}1 M_B$ in the form of a step function.

In the fig. 2, *a)* transition process of a change of EE $M_{el}(t)$ in a mechanical system with an established value $M_{el}(0) = \frac{1}{\gamma} M_{Ea}(0) = 0{,}084$ is presented. In the fig. 2, *b*) transition processes of a change of moment in EE M_{el} (relationship 1) and moment of an electric drive M_D (relationship 2) with synthesized OFC in the initial system with inertialess force sensor with $T_{SF} = 0$ .In the fig. 2 an overcontrol of moment in EE in mechanical system without an electric drive was 83 %, and in the system with OFC in fig. 2, *b*) – 15 %, i.e. in 5.5 times less. An implementation of synthesized OFC allowed to decrease static error of force control in 36.5 times.

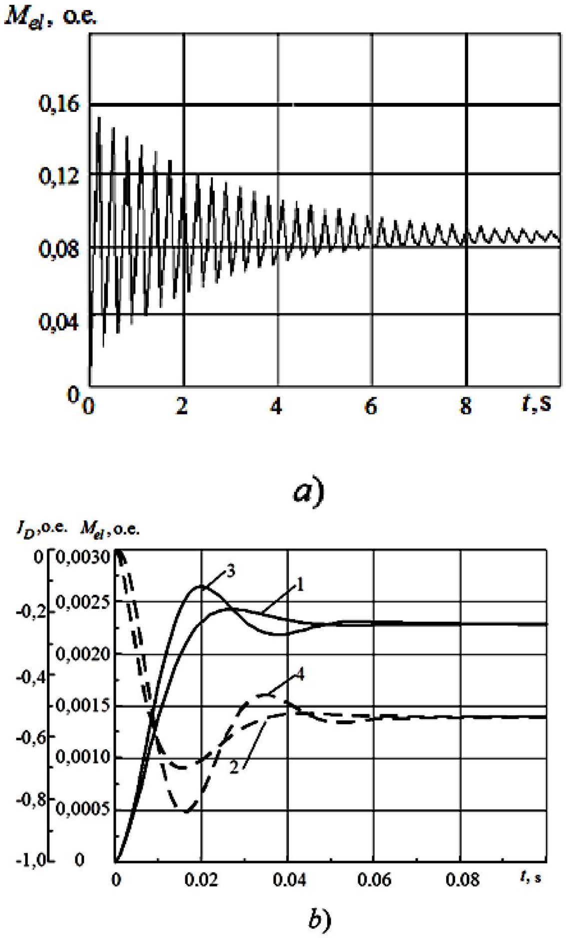

Fig.2. Transition processes in the studied EMS with EL

An analysis of the processes in EMS with EL in a case of using inertial force sensor efforts [17] with transfer function in a form of an aperiodic link with time constant $T_{SF} = 0{,}002$,is presented in fig. 2*b*) in a form of values M_{el} (relationship 3) and moment of drive M_D (relationship 4). Conducted studies have shown a possibility of an increase of maximum values of moment M_{el} and moment of a drive M_D in a case of an emerge of inertial elements in the feedback circuit by force, which must be taken into account during an implementation of FCS.

Completed studies have shown effectiveness of synthesized OFC in EMS with EL during changes of perturbation actions. The proposed method for synthesis of OFC in EMS with EL had been tested during a development of training simulator "Exit 2", designed for a training of astronauts for a work in a condition of zero gravity, systems [18] and balanced manipulators of MP100 type [3].

Discussion

With an implementation of optimal control theory in the studies [11: 19-21] problems of minimization of fluctuations in EMS with EL were discussed. At that, studies, performed with the systems of subordinate regulation of coordinates of ED [22, 23] were of the most interest. However, during an implementation of those systems feedback by speed, but not at by moment of EE, as in the present case, was used. Therefore, the proposed method of optimal force regulator's synthesis supplements methodology of a solution of problems of automated systems' optimal control, presented in scientific works [24, 25]. Practical results of conducted studies conform to the results obtained during synthesis of regulators and corrective devices in EMS with EL, which are ensuring optimum vibration damping of elastic mechanisms [26, 27].

Conclusion

A solution of the problem of optimal synthesis force regulator was completed using a linearized mathematical model of FCS and with assumptions about not considering inertia of measurement devices, a description of properties of closed circuit of an electric drive's current with an aperiodic link the of first order. In further research it is necessary to carry out studies with an implementation of more precise mathematical models and to practically assess an impact of the assumptions made on effectiveness of obtained results.

Acknowledgments

The results of the presented study were obtained with the support of project # 2878 "The development of theoretical and practical aspects of a creation of electrotechnical systems of training simulators and mobile objects", which is conducted in the main part of the state project #2014/143 the Ministry of Education and Science of the Russian Federation.

Corresponding Author:
Dr.Pyatibratov Georgy Yakovlevich
Federal State Budget Educational Institution of Higher Professional Education
Platov South-Russian State Polytechnic University (NPI)
Prosveshcheniya Street, 132, Novocherkassk, 346428, Russia

References

1. Pyatibratov, G.Ya., 1995. Status, problems and ways to improve systems for weightlessness simulation ground testing of space technology products. Izv. vuzov. Sev.-Kavk. Region. Tekhnicheskie nauki. [Proceedings of the Universities. North-Caucasus region. Technical sciences], 3-4: 39-49 (in Russian).
2. Pyatibratov, G.Ya., O.A. Kravchenko and V.P. Papirnyak, 2010. Methods and ways of improving the implementation of simulators to train astronauts to work in weightlessness. Izv. vuzov. Electromekhanika. [Proceedings of the Universities. Electromechanics], 5: 70-76 (in Russian).
3. Sukhenko, N.A. and G.Ya. Pyatibratov, 2010. Improving management systems balanced manipulators. Izv. vuzov. Electromekhanika. [Proceedings of the Universities. Electromechanics], 5: 77-81 (in Russian).
4. Pyatibratov, G.Ya., 1998. Principles of design and implementation of force controlling systems in elastic gears electromechanical systems. Izv. vuzov. Electromekhanika. [Proceedings of the Universities. Electromechanics], 5-6: 73-83 (in Russian).
5. Kravchenko, O.A., G.Ya. Pyatibratov, N.A. Sukhenko and A.B. Bekin, 2013. Principles of design and implementation of compensation systems gravity. Izv. vuzov. Sev.-Kavk. Region. Tekhnicheskie nauki. [Proceedings of the Universities. North-Caucasus region. Technical sciences.], 2: 32-35 (in Russian).
6. Polyakov, L.M. and P.E. Kheruntcev, 1979. Optimal control of dynamic processes in electric drives with elastic couplings. Elektritchestvo [Electricity], 3: 40-45 (in Russian).
7. Kalman, R.E., 1960. Contributions to the Theory of Optimal Control. Bullet. Soc. Mat. Mech., 1(5): 102-119.
8. Koditkschek, D.E., 1992. Task encoding: toward a scientific paradigm for robot planning and control. Robotics and Automation systems, 1(9): 5-39.
9. Kanayama, Y. and S. Yuta, 1985. Computer architecture for intelligent robots. J. Robotic Sys., 3(2): 237-252.
10. Zadeh, L.A., 1983. The Role of Fuzzy Logic in the Management of Uncertainty in Expert. Fuzzy Sets and Systems, 11: 199-227.
11. Petrov, Yu.P., 1977. Variatcionnye metody teorii optimalnogo upravleniya [Variational methods of optimal control theory]. St.-P.: Energy Publ., pp: 280.
12. Pyatibratov, G.Ya. and O.A. Kravchenko, 1997. Implementation of force controlling system Electromechanical systems with elastic couplings. Izv. vuzov. Electromekhanika. [Proceedings of the Universities. Electromechanics.], 3: 51-54 (in Russian).
13. Kravchenko, O.A., D.Yu. Bogdanov and D.V. Barylnik, 2014. A mathematical model of multi-axis force compensation electromechanical system. Vestnik YUUrGY. Seriya “Energetika”, 1(14): 71-78.
14. Petrov, Yu.P., 1987. Synthesis of optimal control systems with incompletely known perturbing forces. St.-P.: St.-P. University Publ., pp: 292.
15. Kravchenko, O.A. and G.Ya. Pyatibratov, 1998. Synthesis of optimal control in Electromechanical systems with elastic couplings. Izv. vuzov. Electromekhanika. [Proceedings of the Universities. Electromechanics.], 4: 58-63 (in Russian).
16. Kravchenko, O.A., 2013. Multicriteria method of determining the rational parameters of electric drives the force compensation systems. Izv. vuzov. Electromekhanika. [Proceedings of the Universities. Electromechanics.], 2: 32-35 (in Russian).
17. Kravchenko, O.A., 2010. Features of construction and implementation of information-measuring and control systems the force compensation systems. Izv. vuzov. Sev.-Kavk. Region. Tekhnicheskie nauki. [Proceedings of the Universities. North-Caucasus region. Technical sciences], 2: 47-52 (in Russian).
18. Kravchenko, O.A., 2008. Creating and operating experience the force compensation systems provide versatile training astronauts to work in weightlessness. Izv. vuzov. Electromekhanika. [Proceedings of the Universities. Electromechanics.], 2: 42-47 (in Russian).
19. Rogov, N.I., 1998. Optimal motor control robot with an elastic element]. Izv. AN SSSR. Tekhnicheskaya kibernetika. Proceedings of the

academy of sciences USSR. Technical cybernetic, 1: 135-145.

20. Wiss, Z., 1989. Zcitoptimule Steuerung von Antriebssystemen mit elustischer Mechanik. Riefenstahl ulrich, Ha Nguyen Hong, Sanchez Jorge Bermuder. Techn. Univ. Otto von Guericke, Magdeburg, 7(33): 137-142.
21. Petrov, Yu.P. and E.A. Yarv, 1990. Optimization of electric drives with flexible couplings, taking account of friction. Electrical Technology, 4: 26-33 (in Russian).
22. Roatz, E., 1975. Einfluβ von mechanischen Schwrigungen auf das dynamische Verhalten von gegten Antriben. Mess-Stenern-Regeln, 7(18): 252-253.
23. Speth, W., 1968. Drehzahlegel Kreise mit periodischen Laständerungen oder mit elastich qekuppelter Arbeitsmaschine. Seimens-Zeitschrift, 2(42): 116-122.
24. Petrov, Yu.P. and V.A. Siverin, 1985. Optimization of electric drives with flexible and elastic couplings. Electric Technology, USSR, 1: 95-101.
25. Burgin, B.Sh., 1998. Synthesis of the two-mass electromechanical system of the shaft torque stabilization. Elektrichestvo, 2: 49-54.
26. Pyatibratov, G.Ya., 1997. Optimization of electric damping of mechanical vibrations of elastic under the action of force disturbances. Optimisatciya rezhimov raboty system elektroprivodov. Mezhvuz. sb. Krasnoyarsk. [Interuniversity collection], pp: 48-53.
27. Pyatibratov, G.Ya. and I.V. Hasambiev, 2007. Optimization of passive electric drive damping of elastic vibrations executive bodies balanced manipulators. Izv. vuzov. Electromekhanika. [Proceedings of the Universities. Electromechanics], 3: 29-34 (in Russian).

7/19/2014