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MATHEMATICAL MODELLING AND EXPERIMENTAL DETERMINATION OF PARAMETERS OF THE GUIDANCE SYSTEM OF WEAPONRY COMPLEX

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Abstract: The methodological approaches to the improvement of the control system of the vertical guidance mechanism of FM-21 multiple launch missile system to increasing its speed and positioning accuracy are confirmed. The use of the three-circuit positional structure of the control system of the guidance mechanism with a position control loop and a fuzzy corrector is justified. A mathematical model of the guiding package motion has been obtained and its reaction has been calculated. The parameters of the electrical and mechanical elements of a guidance system and their transient characteristics are experimentally obtained. With the use of the approximation procedure, the analytical dependencies of these transient characteristics and corresponding transient functions of various orders of the elements of an electric drive power circuit are obtained.

Key words: guidance system, positioning accuracy, mathematical model, dynamics, statics, speed control

1. Introduction

Modern electro-mechanical systems of positioning and monitoring require specific advanced parameters of operating speed, static and dynamic positioning accuracy, the character of transient process, power characteristics, the level of automation etc. It is possible to improve these factors only on the basis of complex systematic approach, and the best optimal solutions with the use of above mentioned approach can be obtained by mathematical and computer modelling.

Performing the optimizing procedures on the computer models taking into account the limitations of the parameters, factors and coordinates of electro-mechanical system being designed will enable obtaining the structural, systemic and technical solutions and optimal values of variables for thorough realization of requirements set to dynamic and static factors of positional guidance system.

Formulation of the problem. The task of the synthesis of an electro-mechanical system of a motion drive for the guiding package of a weaponry complex consists in searching the structure and parameters of a complex dynamic system, which in general case consists of such four units:

- operating mechanism;
- transmitting device;
- drive motor;
- automatic control system.

Obtaining high parameters of positioning accuracy, operational speed, adjustment of input and temporary coordinates and reliability of the electro-mechanical guiding system fulfilling the requirements of weight and dimensions could be achieved only under the condition of thorough implementation of the potential of modern circuit design and the potential abilities of all interacting units of electro-mechanical guiding system. The development of a structure being rational or optimal by some factors and determination of the values of parameters of the guidance system will create the possibility of achieving the required technical and economical effect.

Analysis of resent research and publications. The analysis of known approaches and results of modern investigations of electro-mechanical guiding systems shows that all of them in general apply classical tools, methods and approaches of the theory of automatic control, which are based on linear (or linearized in some states or adjacency of working points) analogue or discreet models of fixed structure. With such an approach, the process of taking into account great numbers of nonlinearities existing in the elements of mechanical units, transmitting elements and in the automatic control system (ACS), some of them being quite essential, becomes rather difficult. This also concerns the changes of the parameters of electro-mechanical guiding system and load characteristics.

For this kind of drives, it is necessary to create quite accurate non-linear dynamic models and relevant automatic control systems (ACS). Therefore, for such systems, the methods of changing the optimal transmission ratio of the reduction gear [1] for the minimization of regulation time are proposed. In addition, conversion to the effective algorithms of digital control are proposed for dynamics optimization including fuzzy control and neural network control, as well as using the digital models of the monitors of coordinates and parameters [2].

Successful solving the set task of the concerted synthesis of dynamic system consisting of several interacting and interconnected component subsystems requires using modern methods of the theory of automatic control and special design and research methods adequate to the peculiarities of the positioning system of a guidance mechanism [3, 4].

The complexity of the electromechanical guiding system consists in the presence of resilient elements, such as a torsion, play of a mechanical transmission, change of parameters and inertia moment of a kinematic diagram, the moment of static load in the guiding process. According to this, the synthesis of such a system with taking into account all mentioned above parameters and basing on the classical approaches is not possible. Moreover, the adaptation of the characteristics of dynamics of the guiding system to the changes of mentioned above factors is also quite difficult.

In our opinion, a reasonable approach for obtaining the required dynamics and statics of the guiding system, possessing non-linear characteristics, changes in parameters and disturbances mentioned above, is applying a modern methodology and circuit design of intellectual guidance, in particular, the systems of fuzzy output and fuzzy regulators.

The dynamic system of the guiding mechanism developed on the basis of such an approach will function correctly not only in the adjacency of the point of most likely positioning, but it will also fulfill requirements imposed on the dynamic and static indicators in the whole space of states, which in turn consists of ranges of fluctuation of parameters and disturbing factors of the dynamic non-linear guidance system.

One of such reasonable approaches to the investigation of dynamic and static properties of such a system with the non-linear descriptive model is mathematical and computer modeling of its modes. Arranging relevant mathematical experiments and performing computer model investigations will enable thorough investigating the stability and dynamic and static indicators during the starting and braking operation modes in the real areas of the changes of setting and disturbing factors, including parametrical changes in the mechanism of vertical guidance of the guiding package.

All mentioned above proves that the improvements of existing structures of the electro-mechanical guidance system of the weaponry complex and creating new more advanced ones are topical and reasonable. These new structures must meet the strict modern requirements imposed on the indicators of dynamics, statics, power efficiency, reliability and compactness, as well as the methodology for their computer synthesis, optimization, adaptation and analysis on the basis of high- accuracy non-linear models of the guidance systems, taking into account limitations to the ranges of its coordinate changes and real parameter and coordinate disturbances.

The aim of the article is to obtain the parameters of the elements of the electrical and mechanical parts of the guidance system and the range of their changes for creating its mathematical and computer model.

2. Research results

Described above investigations were conducted for the vertical guidance mechanism of an artillery unit of the weaponry complex FM-21. In Fig. 1, the obtained design model of the mechanical unit of the FM-21 vertical guidance mechanism is shown.

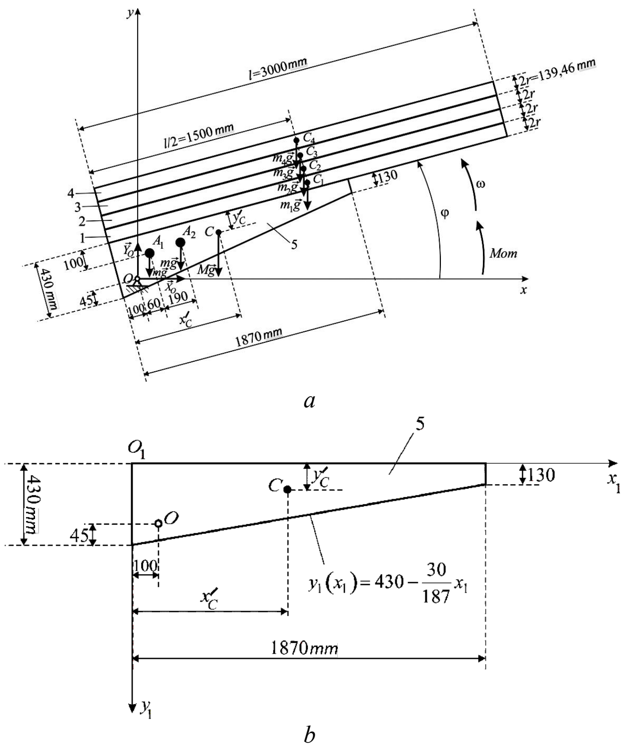


Fig.1. Design model of the mechanical unit of the vertical guidance mechanism of an artillery unit of the weaponry complex FM-21.

The existing electro-mechanical system of the guidance mechanism operates on the basis of electric drive according to the layout “dynamoelectric amplifier – direct current motor” (DEA - DCM).

The dynamoelectric amplifier ЕМП-12ПМ (DEA-12DM) is a single-case unit consisting of a generator, constructed with the use of a two-stage transverse field amplifier and a drive direct current motor: U_n=110 V, P_n=2.2 kW, I_n=18A, n_n=6000±600 rpm. An actuating motor МИ-22 is a four-pole reversing direct current motor with independent excitation: U_n=110 V, P_n=2 kW, n_n=4750 rpm.

In the existing electro-mechanical system (EMS) of setting the guiding package in motion, armature current feedbacks of the actuating motor and voltage feedbacks of the rotary cross-field amplifier are used. The automatic control of the position of the guiding package is not provided. The use of the rotary amplifier with the drive motor increases weight and dimensions of EMS, provides rather low operation speed, makes exploitation and maintenance more difficult, etc.

The mechanical part of this EMS has limited rigidity due to the torsion, plays and gaps in a mechanic gear. These factors make it impossible to obtain high accuracy and guidance speed of the guiding package and cause considerable increase in weight and dimensions, as well as the maintenance difficulties.

For improving mentioned above performance characteristics, the upgrade of guiding EMS of FM-21 on the basis of replacing the transforming unit with DEA by a pulse width converter using the automatic control system (ACS) with the circuit of position adjustment and the fuzzy corrector [3].

As a result of the analysis of technical documentation, experimental investigations and the measurements of the artillery unit of fighting machine FM-21, design models and distribution diagrams of the forces and moments of gun cradles of the vertical guidance mechanism of guiding package were obtained, as it is shown in Fig. 1 and Fig. 2.

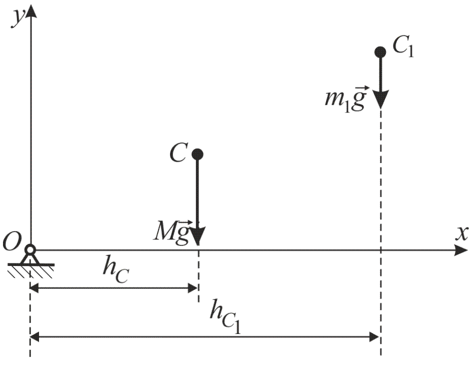


Fig. 2. Distribution diagram of weight forces $M\vec{g}$ and $m_1\vec{g}$

The main parameters of the design model of the vertical guidance mechanism are as follows:

$l = 3m$ is the length of guiding package;

$r = 0.6973\ m$ is an outer radius of the guide;

$m = 180\ kg$ is a torsion mass;

$m_1 + m_2 + m_3 + m_4 = 885\ kg$ is a mass of guiding package (4 rows of 10 guides each);

$M = 1100\ kg$ is gun cradle weight;

$Mo \cong 56374\ H \cdot m$ is a moment which should be developed for lifting the guiding package of the artillery unit of the fighting machine FM-21.

For shown design models (Fig. 1, Fig. 2), the equation of the motion of guiding package has been obtained:

$$J_{zz}\frac{d^2\phi}{dt^2} = M_{om} - mgh_{A_1} - mgh_{A_2} - Mgh_c - \\ -m_1gh_{c_1} - m_2gh_{c_2} - m_3gh_{c_3} - m_4gh_{c_4} \tag{1}$$

Having determined the total moment of inertia of all moving weights relative to the axis O_z basing on the Huygens–Steiner theorem and having performed quite easy mathematical and geometrical transformations, the authors obtained the equation of dynamics of the guiding package [5, 6]:

$$12137.079 \cdot \frac{d^2\phi}{dt^2} = 56374.53 - \\ -5637.2531\cos\phi + 2656.1994\sin\phi. \tag{2}$$

Initial conditions $\phi(0) = 0, \dot{\phi}(0) = 0$ (assuming that at the initial moment the system was in the quiescent state) being taken into account, the solutions to differential equation (2) for different loadings of the guiding package were obtained and their diagrams are shown in Fig. 3.

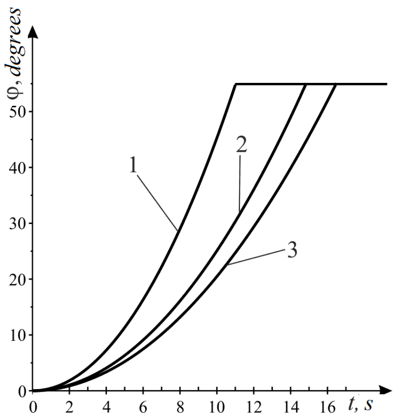


Fig.3. Time dependences of lift angle φ(t) of the guiding package of the fighting machine FM-21, where curve 1 is for a non-loaded package; 2 is for half-loaded package (20 missiles); 3 is for entirely loaded package (40 missiles).

The obtained mathematical model (2) can be used independently for the investigations of the motion dynamics of guiding package in the vertical plane. It can be also integrated into a general mathematical model of the electro-mechanical system of the mechanism of vertical guidance of the guiding package (for the existing system, as well as for the improved one) for solving the task of its structural and parametrical synthesis for obtaining the desirable indicators of the motion dynamics.

On the basis of the obtained transient, the parameters of sections of the structural Simulink model of the electro-mechanical system which sets the guiding package of FM-21 in motion can be determined.

For the verification of the mathematical model obtained above (2), experimental investigations of the vertical guidance mechanism of the FM-21 system were carried out. For their performance, a sensor AS5045-ASSU of angular motion was mounted on the moving and stationary parts of the guiding mechanism. This is the programmed magnetic noncontact rotary 12-bit encoder of SSOP type placed in the 16-terminal case, which is used for measuring angles at 360 degree rotation. During the experiment, different speed and angle values of guiding were set by a control console C6 0901.

For the registration of the time dependencies of electrical drive coordinate changes a digital USB oscilloscope DiSco2 was used during the experiments, which enabled stochastic processing of the experimental curves including the procedures of smoothing, averaging etc.

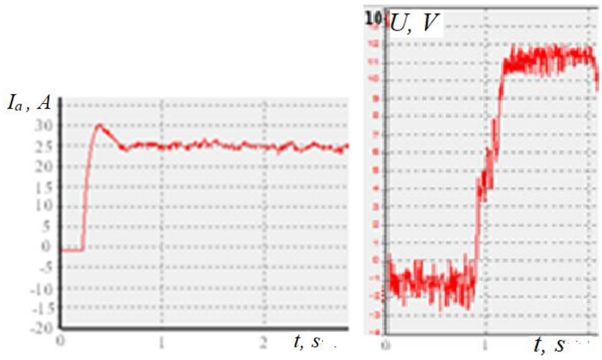
In particular, for obtaining the parameters of the elements of a feeding armature circuit of the DEA-DCM, the transients of the armature current $I_a(t)$ (Fig. 4, a) and DEA voltage (Fig. 4, b) were obtained.

For these experimental transients, their regression time dependencies were obtained by the least-squares method. Their graphs are shown in Fig. 5.

Having performed the direct Laplace transform and the procedure of lowering the order for the time dependencies of transients (Fig. 5), the authors obtain transfer functions for the respective sections of the electro-mechanical system of the guiding mechanism, which are accurate enough for describing their dynamics:

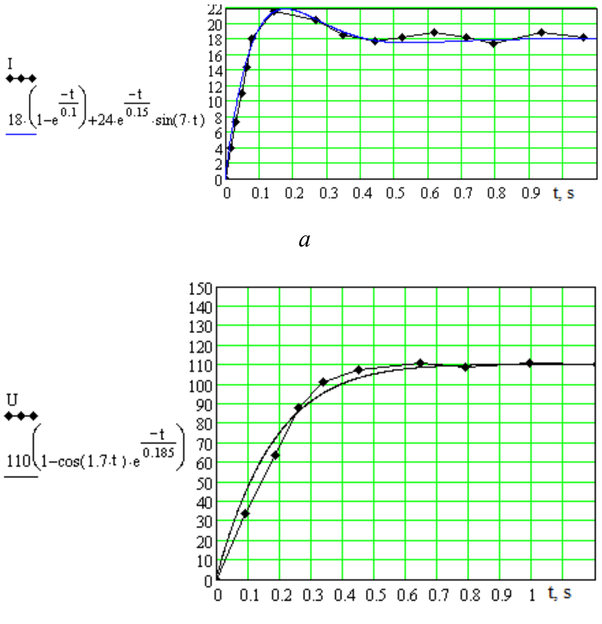
$$W_1(s) = \frac{18{,}686}{0{,}001325 \cdot s^2 + 0{,}036 \cdot s + 1} \tag{3}$$

$$W_2(s) = \frac{110}{0{,}174 \cdot s + 1} \tag{4}$$



a b

Fig. 4. Experimental time dependencies by: a) armature current $I_a(t)$; b) DEA voltage $U_{DEA}(t)$



a

b

Fig. 5. Graphs of approximated experimental transients by a) armature current $I_a(t)$; b) DEA voltage $U_{DEA}(t)$

In the future, the obtained transients will be used for forming the structural Simulink-model of these electrical drive elements of the guiding system of the weaponry complex.

According to the results shown in Fig. 4 and Fig. 5 and the reactions of the structural elements of the guiding system obtained during some other experiments, the parameters of the elements of the power circuit and of ACS drive of DEA-DCM (active resistances, inductances, time constants, static amplification factors etc.) were determined.

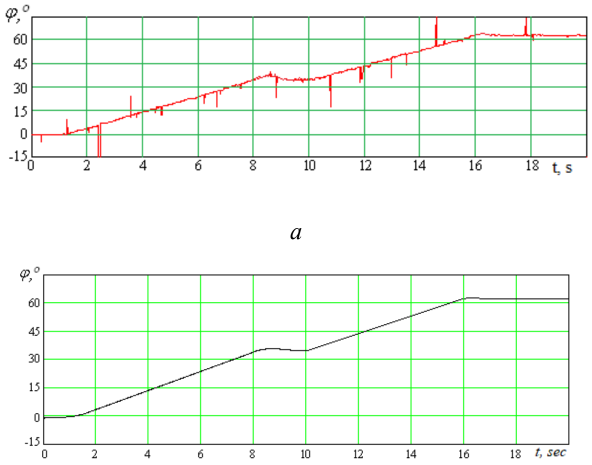
Time dependencies of the process of adjustment of the guidance angle for different controlling speed factors set by the control panel and at different loads of guiding package with missiles were recorded in files. For the registration of the guiding package position the mentioned above position sensor was used.

Below (in Fig. 5, a) the experimentally obtained dependence $\phi_{gp}(t)$ of the shift of a non-loaded guiding package by a maximum angle with maximum speed with an intermediate stop in the middle of this angle is shown. The analysis of the dependency shows that during positioning by the angle $\phi_{gp} \cong 35^o$ overregulation $\Delta\varphi \cong 6.5\,\%$ occurs. When shifting by other angles, overregulation was changing in the range $\Delta\phi \cong 0...8\,\%$. This can be explained by the complex action of torsion, gaps, play in the reducer and non-rigid mount of the gun cradle of the artillery unit. Furthermore, at positioning at the maximum angle, overregulation is so small that it can be neglected, since at this angle the torsion becomes non-loaded, and its acting is major. The mathematical model of such a mechanical system should be considered as a two-mass one [9-12].

In Fig. 6, b the approximated time dependency $\varphi_{gp}(t)$ for maximum speed of shifting the non-loaded guiding package to the maximum guidance angle corresponding to the experimental one is presented.

Below, the approximating analytical dependency $\varphi^a_{gp}(t)$ obtained for the experimental dependency $\varphi^a_{gp}(t)$ serving for the description of the processes of acceleration, motion and deceleration at the half-angle in the time period $t \in [0, 10]$ is shown:

$$\phi^a_{gp}(\mathrm{t}) = \begin{cases} 0, & \mathit{if} \quad 0 \le t \le 1.75; \\ 4.423 \cdot t - 1.846, & \mathit{if}\ 1.75 \le t \le 8; \\ 5.248 \cdot \sin(t - 1.226) + 31.727. \end{cases}$$



b

Fig. 6. a) experimental and b) approximated time dependencies of the guidance angle $\varphi_{gp}(t)$ *of guiding package*

On the basis of analytically and experimentally obtained reactions $\phi_{gp}(t)$ of the guiding mechanism, conducting the optimizing procedure of the determination and adjustment of the parameters of a two-mass kinetic model of the guiding mechanism is being planned with the use of the Optimization add-in of the Matlab software. In particular, this will include adjusting the dependencies of the weight moments of inertia, the moment of static load and resilience of the torsion on the angle change $\phi_{gp}(t)$ for using it in the structural Simulink model of the electro-mechanical system of the guiding package of the fighting machine FM-21.

3. Conclusions

1. The direction and methodology of improving the control system of the guidance mechanism of the guiding package for increasing the operating speed, positioning accuracy and decreasing its weight and dimensions, as well as costs were substantiated.

2. With the use of the results of the experimental investigations, the mathematical models of particular units and parameters of the elements of electrical and mechanical parts of the guidance mechanism of the guiding package of the fighting machine FM-21 were obtained.

3. For the automation of the guiding process, the use of the 3-circuit structure of the control system of the guiding mechanism with the circuit of position regulation (the angle of the guidance of the guiding package) with the fuzzy regulator was justified.

4. The reasonability and the technique of the optimization of the determining the parameters and characteristics of the guidance mechanism were substantiated while creating the structural Simulink model of the positional ACS by the guidance of the guiding package with the use of mathematical and computer modelling for investigating the dynamics and statics of the guiding process of the fighting machine FM-21.

References

[1] N. Prismotrov, Y. Ponomarev, and E. Pirovskikh, “Choosing the optimal gear ratio for maximum fast life”, *All-Russia Annual Scientific and Practical Conference: Collection of Materials “Society, Science, Innovation”* (NPK-2013), pp. 1146–1147, 2013.

[2] L. Blokhin, N. Sitnichenko, and V. Kukhar, “New problems and algorithms for synthesis of optimal structures of observers of the original coordinates of moving objects”, *Problems of Informatization and Management*, vol. 40, No. 4, pp. 19–23, 2012.

[3] O. Shyko, “Simulation of joint motion of a rocket projectile and a mobile launcher MLRS”, *Weapons systems and military equipment,* vol. 38, No. 2, pp. 44–60, Kharkiv: HUPS, 2014.

[4] V. Kuntsevich, *Uncertainty management: Guaranteed results in management and identification tasks*. Kiyv, Ukraine: Naukova Dumka, p. 264, 2006.

[5] L. Lojciansky and A. Lurie, *Course of Theoretical Mechanics*. M.: Science. p. 420, 1982.

[6] V. Biderman, *Theory of mechanical oscillations*. M.: Higher school. p. 408, 1980.

[7] A. Rutkovsky, L. Matveeva, and G. Kozachek, “Optimization of coefficients of the transfer function obtained by the modified Sima method on an experimentally filmed transient response”, *Herald VGTU*, No. 3, 2010.

[8] A. Alikov, M. Kovaleva, A. Rutkovsky, and N. Tedeeva, “Automation of optimal identification of transfer functions of dynamic elements of

complex technological objects by acceleration curves”, *Herald DSTU.* Engineering sciences, no. 2, 2017.

[9] A. Smilgevicius and R. Rinkeviciene, “Simulation of transients in the mechanical part of electromechanical system”, in *Proc. 10th International Conference MMA2005&CMAM2, Trakai,* pp.155–162, 2005.

[10] S. Bolognani, A. Venturato and M. Zigliotto, “Theoretical and experimental comparison of speed controllers for elastic two-mass-systems”, in *Proc. IEEE 31st Annual Power Electronics Specialists Conference, PESC2000, 18- 23 June 2000,* vol. 3, pp. 1087–1092, 2000.

[11] M. Feiler, C. Westermaier and D. Schroder, “Adaptive speed control of a twomass system”, in *Proc. IEEE Conference on Control Applications CCA2003, 23–25 June 2003,* vol. 2, pp. 1112–1117, 2003.

[12] M. Gernet and V. Ratobylsky, *Determination of moments of inertia.* M: Mechanical Engineering. p. 246, 1969.

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ТА ЕКСПЕРИМЕНТАЛЬНА ІДЕНТИФІКАЦІЯ ПАРАМЕТРІВ СИСТЕМИ НАВЕДЕННЯ КОМПЛЕКСУ ОЗБРОЄННЯ

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Обґрунтовано методологічні підходи до удосконалення системи керування механізму вертикального наведення пакету напрямних реактивної системи залпового вогню БМ-21 у напрямі підвищення швидкодії та точності позиціювання. Обґрунтовано використання триконтурної позиційної структури системи керування механізмом наведення з контуром регулювання положення та нечітким коректором. Отримано математичну модель руху пакету напрямних та розраховано їх реакцію. Експериментально отримано параметри елементів системи наведення, їхні перехідні характеристики та передавальні функції.

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