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IDENTIFICATION OF THE SIGNALS IN POSITION CONTROL CIRCUITS OF A HEXAPOD PLATFORM

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Abstract*—*The paper deals method of identification useful signals, the disturbance and interference operating hexapod platform management system for modeling large-scale marine spatial pitching ship.

Index Terms—stand-simulator; stabilization system; frequency response; hexapod; accelerometer; spectral density; amplitude and phase frequency characteristic.

I. INTRODUCTION

The platform of a hexapod is intended for commission of the movement on a spatially set trajectory. Accuracy of a platform's navigation is largely determined by a structure and parameters of a control system. As it is known from [1] the highest positioning accuracy can be achieved only in the optimal control system. A necessary condition for a successful synthesis of such the control system is an existence of a control object's model, which is obtained under actual operating conditions. The first step on the way of obtaining this model is identification of dynamics of signals in position control circuits of the hexapod platform.

Analysis of the results [2], [3] showed that the existing models of dynamics of signals were got as a result of mathematical modeling of a work of the hexapod's control system. A main disadvantage of these models is to ignore the dynamics of the rods drives. Therefore, the task of studying the dynamics model of a hexapod together with drives on the base of an experimental data – is relevant.

II. PROBLEM STATEMENT

The purpose of this research is to identify the matrix of transfer functions of a system "hexapod-regulator", which characterizes an influence of a program acceleration vector r on an actual acceleration vector **x**, which is measured with the help of 3D MEMS accelerometer, as well as the matrix of spectral densities of disturbances, which aren't measured.

To achieve the objective has been developed and mounted the experimental plant (Fig. 1). The plant consists of the hexapod with an actuator *1* and a movable platform *2*. An origin of the coordinate system *x*, *y*, *z* is associated with a center of mass of the platform. A 3d MEMS accelerometer with sensitive axes oriented along the axes of the base *x*, *y*, *z* is mounted on the platform. The actuators *1* are brushless DC motors controlled by a computer-integrated control system *3*.

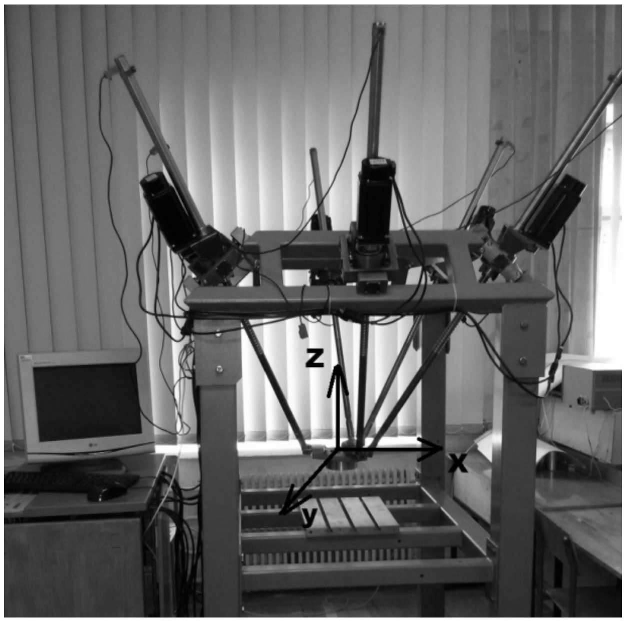

Fig. 1. Machine-hexapod with installed 3D MEMS accelerometer

In research [4] is shown that the system "hexapod-regulator" has two inputs and one output (Fig. 2). The vector of program signals r acts on the first input. Its components are equal to the set values of the projections of the platform center of mass acceleration on the axis *x* (r_x) and *y* (r_y)

$$r = \begin{bmatrix} r_x & r_y \end{bmatrix}^{\mathrm{T}}, \tag{1}$$

where T is a symbol of a matrix transposition.

A disturbance vector ψ acts on the second input of the system. It also has two components

$$\psi = \begin{bmatrix} \psi_x & \psi_y \end{bmatrix}^{\mathrm{T}}, \tag{2}$$

where ψ_x, ψ_y are projections of the resistance forces on the axis of the coordinate basis x, y, z.

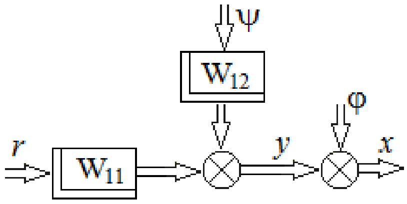

Fig. 2. Block diagram of a multi-dimensional object with a sensor

The systems (Fig. 2) output is denoted as a two-dimensional vector **x**

$$\mathbf{x} = \begin{bmatrix} x_x & x_y \end{bmatrix}^{\mathrm{T}}, \qquad (3)$$

where x_x and x_y are projections of the platform's actual acceleration on sensitivity axis of the 3D MEMS accelerometer mounted on the platform.

Noises of the accelerometer form a vector $\boldsymbol{\varphi}$, which also has two components

$$\boldsymbol{\varphi} = \begin{bmatrix} \varphi_x & \varphi_y \end{bmatrix}^{\mathrm{T}}. \qquad (4)$$

Communication between the vectors (1), (2), (4) and (3) subject to the scheme (see Fig. 2), by analogy to the monograph [1], is characterized by the following system of ordinary differential equations

$$\mathbf{P}x = \mathbf{M}r + \psi - P\varphi, \qquad (5)$$

where **P** and **M** are polynomial matrixes of differentiating operator $p = d/dt$ of 2×2 dimensions. After completing the Laplace transform of the left and right side of the equation (5) with zero initial conditions and multiplying the left and right side of this equation by the inverse matrix $\mathbf{P}^{-1}$ it is formed the following ratio

$$\mathbf{x} - \boldsymbol{\varphi} = \mathbf{W}_{11}\mathbf{r} + \mathbf{W}_{12}\boldsymbol{\psi}, \qquad (6)$$

where $\mathbf{W}_{11}$ is the matrix of transfer functions of the system "hexapod-regulator" that connects the vectors **r** and **x**; $\mathbf{W}_{12}$ is the matrix of transfer functions of the system that characterizes an influence of the vector $\boldsymbol{\psi}$ on the vector **x**.

With a help of the experimental plant (see Fig. 1) it is possible to create and store the implementation of changes in the vectors r and x components as two-dimensional centered stationary random processes. We assume that the characteristics of the noise vector φ have been found as a result of the dynamic certification, as in article [5]. In this case, the identification problem is to find matrices of transfer functions $\mathbf{W}_{11}$ and the $\mathbf{W}_{12}$ as well as the matrix of spectral densities of the vector $\boldsymbol{\psi}$ that minimize the following criteria

$$J = \left\langle \boldsymbol{\varepsilon}^{\mathrm{T}}(\mathbf{t}) R \varepsilon_*(t) \right\rangle, \qquad (7)$$

where $\boldsymbol{\varepsilon}(\mathbf{t})$ is a vector of identification errors, which is equal to

$$\boldsymbol{\varepsilon}(\mathbf{t}) = x(t) - \mathbf{x}_{\mathbf{m}}(\mathbf{t}), \qquad (8)$$

$\mathbf{x}_{\mathbf{m}}(\mathbf{t})$ is a vector of signals at the output of the system model; **R** is the weighting positively-definite matrix; <*> i sa symbol of Hermitian conjugation [8].

III. Identification Algorithm

It is proposed to carry out three phases of research in order to solve the problem. The aim of the first phase of the research is to identify the characteristics of signals (1) and (3). The second phase is devoted to identification of transfer functions matrices $\mathbf{W}_{11}$ and $\mathbf{W}_{12}$. The aim of the third phase is to verify the obtained models of the signals, the system and disturbances.

We have used a combination of a form filter method [5] and the Blackman–Tukey algorithm [6] in order to fulfill the first phase of the research. In accordance with this on the first stage of the research first of all it is necessary to synthesize the matrix of transfer functions **G** of a filter-former. As shown in [5] for the synthesis of the matrix **G** it must be performed a factorization of the transposed matrix of spectral densities of the vector **r**

$$\mathbf{G}\mathbf{G}_* = S'_{rr}. \qquad (9)$$

One of factorization algorithms is described in detail in the article [9]. Than with the help of the filter-former **G** it is necessary to form the vector **r** (see Fig. 2) and to get records of the vectors (1) and (3) components.

After this as a result of usage the Blackman–Tukey algorithm one should find unbiased and consistent estimates of spectral and cross-spectral densities of all components of the vectors r and x. Than one should run approximation method of logarithmic frequency characteristics of the estimates [1] in order to form transposed matrices of spectral and cross-spectral densities S'_{rr}, S'_{xx}, S'_{xr} and S'_{rx}.

In the framework of the second phase of research one should be used the method of structural identification of linearized models of the dynamics of the multidimensional object contained in the monograph [1]. In accordance with this method, a block matrix of transfer functions **W**

$$\mathbf{W} = \begin{bmatrix} \mathbf{W}_{11} & \mathbf{W}_{12} \end{bmatrix}, \qquad (10)$$

that minimizes the quality criteria (7) can be found from the equation

$$\mathbf{W} = \mathbf{R}_0^{-1}\left(\mathbf{K}_0 + \mathbf{K}_+\right)\mathbf{D}^{-1}, \tag{11}$$

where $\mathbf{R_0}$ is a numerical matrix, which is found as a result of the Cholesky decomposition of the weight matrix $\mathbf{R}$; $\mathbf{K_0} + \mathbf{K_+}$ is a rational matrix of complex variable s, which is a result of the Wiener separation [9] of the following matrix product

$$\mathbf{K}_0 + \mathbf{K}_+ + \mathbf{K}_- = \mathbf{R}_0\mathbf{S}'_{\mathbf{yx}}\mathbf{D}_*^{-1}, \tag{12}$$

$\mathbf{D}$ is analytical in the right half of the complex variable matrix, which is found as a result of the Wiener factorization [10] of the transposed matrix of spectral densities

$$\mathbf{D}\mathbf{D}_* = \mathbf{S}'_{\mathbf{yy}}; \tag{13}$$

$\mathbf{S}'_{\mathbf{yy}}$ is the transposed matrix of spectral densities which is found as a result of the first phase of research

$$\mathbf{S}'_{\mathbf{yy}} = \begin{bmatrix} \mathbf{S}'_{\mathbf{rr}} & \mathbf{O_2} \\ \mathbf{O_2} & \mathbf{E_2} \end{bmatrix}, \tag{14}$$

$\mathbf{O_2}$ is a zero matrix of 2 × 2 dimension; $\mathbf{E_2}$ is the identity matrix of 2 × 2 dimension; $\mathbf{S}'_{\mathbf{yx}}$ is the transposed matrix of cross-spectral densities, which is formed in accordance with a rule

$$\mathbf{S}'_{\mathbf{yx}} = \left[\mathbf{S}'_{\mathbf{rx}} \quad \mathbf{S}'_{\mathbf{\Delta x}}\right], \tag{15}$$

in which the matrix $\mathbf{S}'_{\mathbf{\Delta x}}$ is equal to the transposed result of the Wiener factorization of the following sum

$$\mathbf{S}_{\mathbf{x\Delta}}\mathbf{S}_{\mathbf{\Delta x}} = \mathbf{S}_{\mathbf{xx}} - \mathbf{S}_{\mathbf{xr}}\mathbf{S}_{\mathbf{rr}}^{-1}\mathbf{S}_{\mathbf{rx}}.$$

A theoretical basis of the third phase of the research is the method of simulation [11] implemented using the Simulink Matlab package tool. The usage of this method is possible due to the results of the first and second phases of the research, as well as the block diagram of the modeling process (Fig. 3).

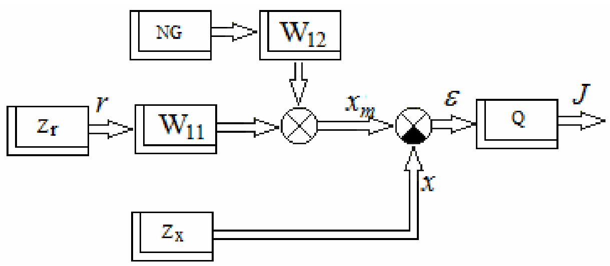

Fig. 3. Block diagram of a simulation model of the system

The simulation model of the system has three inputs and one output. Model inputs consist of r and x vectors records obtained on the first step and stored in Z_r and Z_x blocks, as well as a generator of "white noise", presented by NG unit. The output of the model (Fig. 3) is an estimate of the criteria J, obtained by the calculator Q.

IV. Results

In accordance with the developed algorithm for the problem solution on the first phase of the research it was carried out the identification of control signals in the system (see Fig. 2).

The vector of program signals r with components' records shown in the Fig. 4 has been formed with the help of a computer-integrated system using a filter-former, whose matrix of transfer functions is given in the article [4]. Records of the acceleration signal vector's components obtained by the 3D MEMS accelerometer are shown on the Fig. 5.

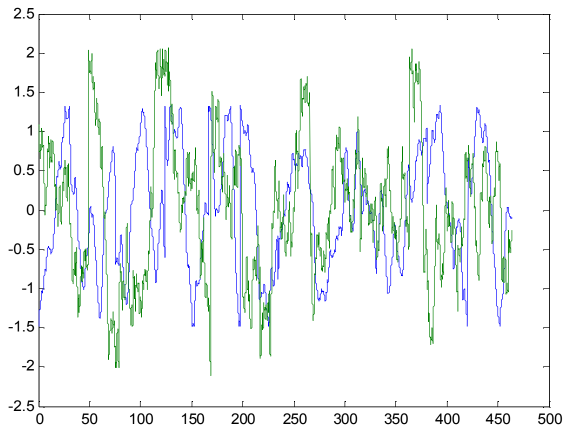

Fig. 4. Records the changes of two components of the vector **r**

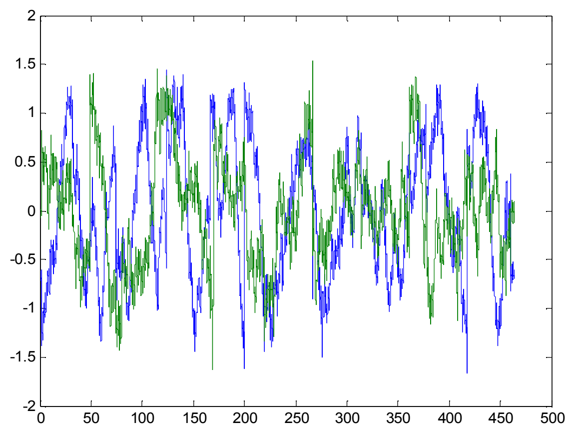

Fig. 5. Responses of the vector components x

As a result of applying the Blackman–Tukey algorithm and subsequent approximation of spectral- and cross spectral densities' estimates are formed the following blocks of transposed matrices (14)

$$\mathbf{S}'_{\mathbf{rr}} = \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix}, \tag{16}$$

where

$$\mathbf{S_{11}} = \frac{0.03\left|s^2\left(s+0.04\right)\right|^2}{\left|\left(s^2+0.016s+2.56\cdot10^{-4}\right)\right|^2} \cdot \frac{1}{\left|\left(s^2+0.01s+0.1\right)\right|^2},$$

$$\mathbf{S_{12}} = \frac{0.013s^3\left(s-0.04\right)\left(s^2-0.06s+0.0036\right)}{\left|\left(s^2+0.1s+0.1\right)\right|^2} \cdot \frac{1}{\left(s^2-0.016s+2.56\cdot10^{-4}\right)\left(s^2+0.04s+0.0025\right)},$$

$$\mathbf{S_{22}} = \frac{0.03\left|\left(s+0.0001\right)\right|^2}{\left|\left(s^2+0.04s+0.0025\right)\right|^2} \cdot \frac{\left|s^2+0.054s+0.0036\right|^2}{\left|\left(s^2+0.01s+0.1\right)\right|^2} \qquad \mathbf{S_{21}} = \mathbf{S_{12*}}.$$

Similarly to the matrix (16), the expression for blocks of the matrix (15) was obtained in the following form

$$\mathbf{S'_{rr}} = \begin{bmatrix} \mathbf{S_{rx1}} & \mathbf{S_{rx2}} \\ \mathbf{S_{rx3}} & \mathbf{S_{rx4}} \end{bmatrix}, \tag{17}$$

where

$$\mathbf{S_{rx1}} = \frac{-0.035(s+0.032)(s-0.04)(s+0.006)}{(s^2+0.0042s+4.9e-05)} \cdot \frac{(s^2-0.001562s+3.368e-05)}{\left|(s^2+0.016s+0.000256)\right|^2\left|(s^2+0.1s+0.01)\right|^2};$$

$$\mathbf{S_{rx2}} = \frac{0.023094(s-9.981e\text{-}05)(s+0.0001002)}{\left|(s^2+0.1s+0.01)\right|^2} \cdot \frac{(s^2-0.013s+8.5e-05)(s^2+0.026s+0.0003)}{(s^2+0.0042s+4.9e-05)(s^2+0.016s+0.000256)} \cdot \frac{(s^2+0.05s+0.0029)(s^2-0.057s+0.0035)}{\left|(s^2+0.04s+0.0025)\right|^2};$$

$$\mathbf{S_{rx3}} = \frac{-0.004(s+0.059)(s-0.04)(s-0.058)}{(s^2+0.0065s+4.2e-05)} \cdot \frac{(s-0.016)(s-0.0008)(s^2+0.029s+0.0017)}{(s^2+0.04s+0.0025)\left|(s^2+0.1s+0.01)\right|^2} \cdot \frac{1}{\left|(s^2+0.016s+0.000256)\right|^2};$$

$$S_{rx4} = \frac{-0.019\ (s-0.0001)\ (s+9.9e-05)}{(s^2+0.0065s+4.2e-05)\ (s^2+0.016s+0.0002)} \cdot \frac{(s^2-0.001s+2.3e\text{-}05)\ (s^2+0.023s+0.0005)}{\left|(s\hat{}2\ +\ 0.04s\ +\ 0.0025)\right|^2} \cdot \frac{(s^2-0.052s+0.0035)\ (s^2+0.05912s+0.004048)}{\left|(s^2+0.1s+0.01)\right|^2},$$

and

$$\mathbf{S'_{\Delta x}} = \frac{1}{\left(s+0.6\right)\left(s+2\right)} \begin{bmatrix} 0.42 & 0.19 \\ 0 & 0.28 \end{bmatrix}. \tag{18}$$

Since components of the vectors **r** and **x** have the same nature the weighting matrix **R** is equal to unit matrix, so the following equation is valid

$$R_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{19}$$

Usage of the equation (11) together with the results (18), (19) made it possible to find a solution of the problem in the form of

$$W' = \begin{vmatrix} W_{11} & W_{12} & W_{13} & W_{14} \\ W_{21} & W_{22} & W_{23} & W_{24} \end{vmatrix}, \tag{20}$$

where

$$W_{11} = 1;$$

$$W_{12} = \frac{\left(-0.23333\cdot\left(s-0.007\right)\cdot\left(s-0.03\right)\right)}{\left(s^2+0.0042s+4.9e-05\right)};$$

$$W_{13} = \frac{0.42}{(s+0.6)(s+2)};$$

$$W_{14} = \frac{0.19}{(s+0.6)(s+2)};$$

$$W_{21} = \frac{\left(0.37477 \times \left(s^2 - 0.02 \times s + 0.0004\right)\right)}{\left(s^2 + 0.0065 \times s + 4.225e - 05\right)};$$

$$W_{22} = 0.6;$$

$$W_{23} = 0;$$

$$W_{24} = \frac{0.28}{(s+0.6)(s+2)}. \tag{21}$$

The resulting matrices (20) and (21) make it possible to start the third stage of research – validating the results of the identification with the help of the simulation method.

In accordance with the block diagram (Fig. 3) is developed a simulation model of the system "hexapod-regulator" (Fig. 6). It consists of the following elements: **NG**-generator of white noise; $\mathbf{Z}_{r1}$, $\mathbf{Z}_{r2}$ are vector software signals that act on the system input; $\mathbf{W}_{11}$ is the matrix of transfer functions "hexapod-regulator"; $\mathbf{W}_{12}$ is the filter-fomer matrix of transfer functions; $\mathbf{Z}_{x1}$, $\mathbf{Z}_{x2}$ is the measured vector **x**; Q is the computer; *J* is the result.

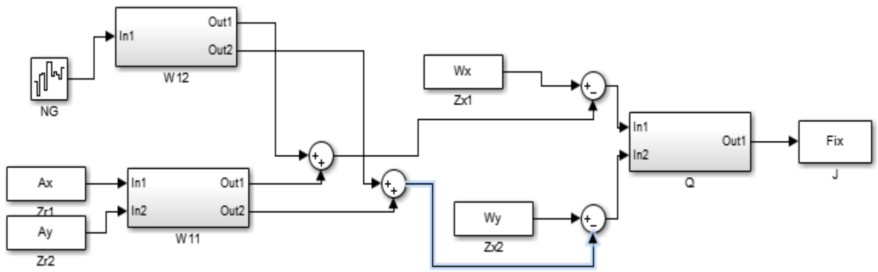

Fig. 6. Simulation model platform-hexapod Sense

As a result of the simulation is set that the system model has been estimated correctly since the identification errors do not exceed 0.3 m\s^{2}of a longitudinal acceleration and 0.3 m\s^2 of a lateral acceleration.

V. Conclusion

Thus, the use of the frequency identification methods allows to obtain not only the linearized models of complex mechatronic objects with several degrees of freedom, but also disturbances, hindering their movement along a predetermined path.

These dynamics models make it possible to formulate and successfully solve the synthesis problem of an optimal hexapod platform control system. Reviewed in the article approach to the identification of useful signals, the disturbance, the noise and the system "hexapod – regulator" provides the data necessary for the further synthesis of the optimal structure of the control system for a multidimensional movable object.

References

[1] V. Azarskov, L Blokhin, and L. Zhytetskiy, *Engineering Methodology of Optimum Systems of Stochastic Stabilization*, Kyiv, NAU, 2006. (in Ukraine)

[2] U. Mamaev and L. Ribak "Construction of mathematical and simulation models of the dynamics of hexapod." *Vibration technology, mechatronics and controlled machines*, Kursk, 2014, pp. 294–300. (in Russian)

[3] M. Melnychenko and S. Osadchy, "Trends of MEMS Technology in UAV," in *Proc. IEEE 3rd Int. Conf. Actual Problems of Unmanned Aerial Vehicles Developments*, APUAVD, Kyiv, October, 13-15, 2015, pp. 66–68.

[4] S. Osadchy, V. Zozulya, and A. Timoshenko. "The Dynamic Characteristics of the Manipulator With Parallel Kinematic Structure Based on Experimental Data," *Advances in Intelligent Robotics and Collaborative Automation*. Chapter 2, River Publishers, 2015, pp. 27–48.

[5] M. Rosyn and V. Bulygyn, *Statistical dynamics theory and the effectiveness of control systems*. Moscow, 1981, 312 p. (in Russian)

[6] R. Otnes, and L. Enokson, *Applied time series analysis*. Moscow, 1982, pp. 410–415.

[7] Bendal J S & Piersol A C. *Random data: analysis and nteasurelnenz procedures*. New York: Wiley, 1971, pp. 296–305.

[8] F. Gantmacher, *Matrix theory* Moscow, Nauka, 1988, 552 p. (in Russian)

[9] F. Aliev, V. Bordug, and V. Larin, *Time and frequency methods of synthesis of optimal controls*. Baku, 1988, 46 p. (in Russian)

[10] M. C. Davis, "Factoring the spectral matrix." *IEEE-Trans. Automat. Cointr.* 1963, AC-8, no. 4, pp. 296–305.

[11] V. Tomashevsky, *Simulation systems*. Kyiv, 2005. 352 p. (in Ukraine)

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М. М. Мельніченко, С. І. Осадчий, В. А. Зозуля. Ідентифікація сигналів в трактах керування платформи гексапода

Проведено ідентифікацію корисних сигналів, збурень і завад, що діють у системі керування платформи гексапода при моделюванні просторової качки крупнотонажного морського судна.

Ключові слова: стенд-симулятор; частотні характеристики; гексапод; акселерометр; спектральні щільності; амплитудно- і фазочастотні характеристики.

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Напрямок наукової діяльності:експериментально-аналітичні методи створенняоптимальних систем автоматичного керування багатовимірними об'єктами, у тому числі нестійкими, при стохастичних впливах.
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Н. Н. Мельниченко, С. И. Осадчий, В.А. Зозуля. Идентификация сигналов в трактах управления платформы гексапода

Проведена идентификация полезных сигналов, возмущений и помех, действующих в системе управления платформы гексапода при моделировании пространственной качки крупнотоннажного морского судна.

Ключевые слова: стенд-симулятор; частотные характеристики; гексапод; акселерометр; спектральные плотности; амплитудно- и фазочастотные характеристики.

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