Tolochko O. *Published in the Journal Electrotechnic and Computer Systems* No. 19 (95), 2015 66 – 70
Electro-Mechanical computer-aided Systems

UDK 621.874:519.876.5+62-83:621.3.078.4

O. Tolochko, ScD.,
D. Bazhutin

SYNTHESIS OF A STATE-FEEDBACK CONTROLLER TO SUPPRESS STRUCTURAL VIBRATIONS OF AN OVERHEAD CRANE

Abstract. *A state-feedback controller is designed on the basis of simplified linear model of overhead crane flexible framework in order to suppress its elastic vibrations. It is shown that standard polynomial synthesis algorithms for a 2D-controller ensure the optimized behavior of the elastic force applied to the trolley, while the input forces are kept at non-zero constant values during movement with constant speed. The presented synthesis of two 1D-controllers allows to avoid the mentioned drawback.*

Keywords: *overhead crane, elastic vibrations, state-feedback controller, polynomial synthesis*

О. И. Толочко, д-р техн. наук,
Д. В. Бажутин

СИНТЕЗ МОДАЛЬНОГО РЕГУЛЯТОРА ДЛЯ ГАШЕНИЯ УПРУГИХ КОЛЕБАНИЙ КОНСТРУКЦИИ МОСТОВОГО КРАНА

Аннотация. *В работе проведен синтез модального регулятора на основе упрощенной линейной модели упругой конструкции мостового крана для гашения ее упругих колебаний. Показано, что стандартные методы полиномиального синтеза двумерного регулятора позволяют оптимизировать переходной процесс упругого усилия, приложенного к тележке, в то время как приводные усилия удерживаются на ненулевом постоянном уровне при движении с постоянной скоростью. Представлен синтез двух одномерных регуляторов, которые позволяют избежать данного недостатка.*

Ключевые слова: *мостовой кран, упругие колебания, модальный регулятор, полиномиальный синтез*

О. І. Толочко, д-р техн. наук,
Д. В. Бажутін

СИНТЕЗ МОДАЛЬНОГО РЕГУЛЯТОРА ДЛЯ ГАСІННЯ ПРУЖНИХ КОЛИВАНЬ КОНСТРУКЦІЇ МОСТОВОГО КРАНУ

Анотація. *У роботі проведено синтез модального регулятора на основі спрощеної лінійної моделі пружної конструкції мостового крану для гасіння її пружних коливань. Показано, що стандартні методи поліноміального синтезу двовимірного регулятор дозволять оптимізувати перехідний процес пружного зусилля, прикладеного до візка, у той же час приводні зусилля утримуються на постійному ненульовому рівні під час руху з усталеною швидкістю. Наведено синтез двох одновимірних регуляторів, які дозволяють уникнути цього недоліку.*

Ключові слова: *мостовий кран, пружні коливання, модальний регулятор, поліноміальний синтез*

Introduction

The typical approach to a control of crane electric drives, whether it is only considering the payload transportation or the anti-sway control as well, is made on an assumption of a crane structure to be rigid [1-4]. Yet the increase of crane dimensions considering the efforts to minimize the construction mass has led to an increase of vibration amplitudes that influence the overall performance of electric drive system. But most importantly it causes the metal fatigue, thus reducing the lifespan of an entire crane unit.

In the recent years this problem has been investigated in a large number of articles. The finite-element method is used for analysis of vertical elastic vibrations of a gantry crane including the payload swing dynamics in [5]. The analysis of structural vibrations of a ship-to-shore container crane in the direction of trolley motion was carried out in [6 – 7]. In [8] an experimental study of gantry stage elastic vibrations is presented, which is considered to be a special case of overhead crane, containing elastic couplings between linear drives and gantry itself.

In [9 – 10] a finite-element model of an overhead crane construction, created in Comsol Multiphysics simulation environment, was simplified to a linear multi-mass system using the spectral analysis of the velocity time diagrams.

One of the known methods of dealing with the elastic vibrations in multi-mass systems is the state-feedback control, which allows shaping the plant response in accordance with the required specifications.

Formulation of the problem

Using the standard polynomial synthesis methods a state feedback controller is to be designed for a given three-mass simplified overhead crane construction model in order to effectively suppress its elastic vibrations.

Research materials

Fig.1 presents a simplified computer model of an elastic overhead crane construction, created in Comsol Multiphysics software, showing the assumed positions of lumped masses with *l* being the distance from one bridge wheel to the trolley center of mass. The simplified mathematical description of such plant as a three mass system, the adequacy of which was shown in [10], is given by the following system of differential equations:

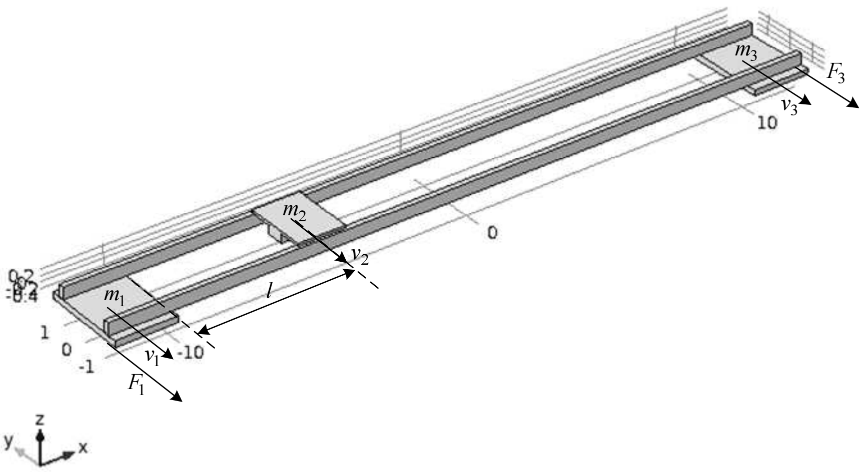

Fig. 1. Mechanical model of an overhead crane in Comsol Multiphysics

$$\begin{cases} m_1 \dfrac{dv_1}{dt} = F_1 - F_{12}, \\ m_2 \dfrac{dv_2}{dt} = F_{12} + F_{32}, \\ m_3 \dfrac{dv_3}{dt} = F_3 - F_{32}, \\ \dfrac{dF_{12}}{dt} = c_{12}(v_1 - v_2), \\ \dfrac{dF_{32}}{dt} = c_{32}(v_3 - v_2), \end{cases} \tag{1}$$

with m_1, m_2, m_3 – lumped masses of bridge wheels and trolley, as shown in Fig.1, with the corresponding linear velocities v_1, v_2 and v_3, F_1, F_3 – applied forces, c_{12}, c_{32} – stiffness factors of elastic couplings between the masses with corresponding elastic forces F_{12} an F_{32}. The corresponding state-space description can be written as follows:

$$s\mathbf{X} = \mathbf{AX} + \mathbf{BU} \tag{2}$$

$$\mathbf{U} = [F_1 \;\; F_3]^{\mathrm{T}}, \quad \mathbf{X} = [v_1 \;\; v_2 \;\; v_3 \;\; F_{12} \;\; F_{32}]^{\mathrm{T}}, \tag{3}$$

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & -1/m_1 & 0 \\ 0 & 0 & 0 & 1/m_2 & 1/m_2 \\ 0 & 0 & 0 & 0 & -1/m_3 \\ c_{12} & -c_{12} & 0 & 0 & 0 \\ 0 & -c_{32} & c_{32} & 0 & 0 \end{bmatrix}, \tag{4}$$

$$\mathbf{B} = \begin{bmatrix} 1/m_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/m_3 & 0 & 0 \end{bmatrix}^{\mathrm{T}}, . \tag{5}$$

A block diagram of the control system with a single state feedback controller is shown in Fig. 2.

The plant model, corresponding to (1), is supplemented with two equal current control loops in form of first-order lag elements with the time constant T_T=0,004.

The goal of the controller design is to determine the feedback gains, so that the poles of the closed loop system:

$$\mathbf{P} = eig(\mathbf{A} - \mathbf{BK}) \tag{6}$$

are placed in the desired points of the complex plane, or the characteristic polynomial of the closed loop system:

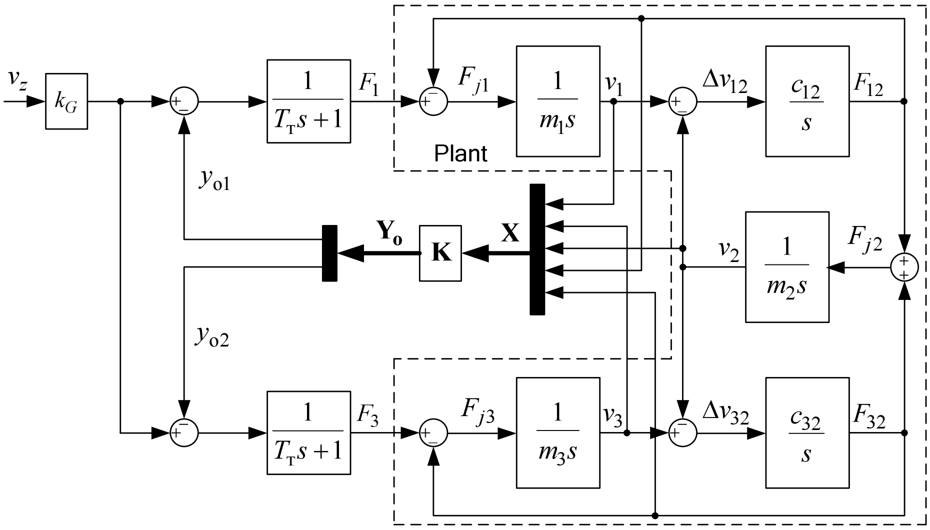

Fig. 2. Block diagram of the closed-loop system with state feedback controller

$$G(s) = \det(s\mathbf{I} - \mathbf{A} + \mathbf{BK}) = \\ = \alpha_5 s^5 + \alpha_4 \omega_0 s^4 + \alpha_3 \omega_0^2 s^3 + \alpha_2 \omega_0^3 s^2 + \\ + \alpha_1 \omega_0^4 s + \omega_0^5 \quad (7)$$

would match the desired standard polynomial with normalized coefficients α_i and the mean geometric root ω_0, which defines the overall performance of control system. The current loops are not taken into consideration during the controller synthesis due to their negligible time lag.

Since the plant model has two inputs and five states, the controller would be a 2 by 5 matrix:

$$\mathbf{K} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} & K_{15} \\ K_{21} & K_{22} & K_{23} & K_{24} & K_{25} \end{bmatrix} = \begin{bmatrix} \mathbf{K_1} \\ \mathbf{K_2} \end{bmatrix}, \quad (8)$$

with the feedback signal:

$$\mathbf{Y}_\text{o} = \mathbf{KX} = \begin{bmatrix} \mathbf{K_1X} \\ \mathbf{K_2X} \end{bmatrix} = \begin{bmatrix} y_{\text{o}1} \\ y_{\text{o}2} \end{bmatrix}. \quad (9)$$

The total gain of the closed loop system would not be equal to unity and has to be corrected via the input gain:

$$k_g = \frac{1}{k_1 + k_3}, \quad (10)$$

with k_1 – closed loop gain for the first plant input, k_3 – closed loop gain for the second plant input. The gain indexes coincide with the corresponding input forces.

The simulation results of a closed loop system with the controller designed so that the poles are placed according to Bessel distribution with the mean geometric root $1/35T_{\text{т}} = 7{,}14$ rad/s are shown in Fig. 3.

It is clear that such control scheme ensures the desired performance of elastic force, applied to the second mass. Yet the movement with constant velocity is performed under the effect of constant input motor forces and elastic forces and of the opposite signs. Since input forces are proportional to the torque-producing current components, this will lead to a drastic increase in copper heat losses. Moreover the crane motion is characterized by a crabbing effect being the displacement difference of the opposite wheel pairs due to the velocity difference during acceleration and deceleration stages. Thus it is obvious, that the standard pole-placement algorithms cannot produce a viable solution for this problem.

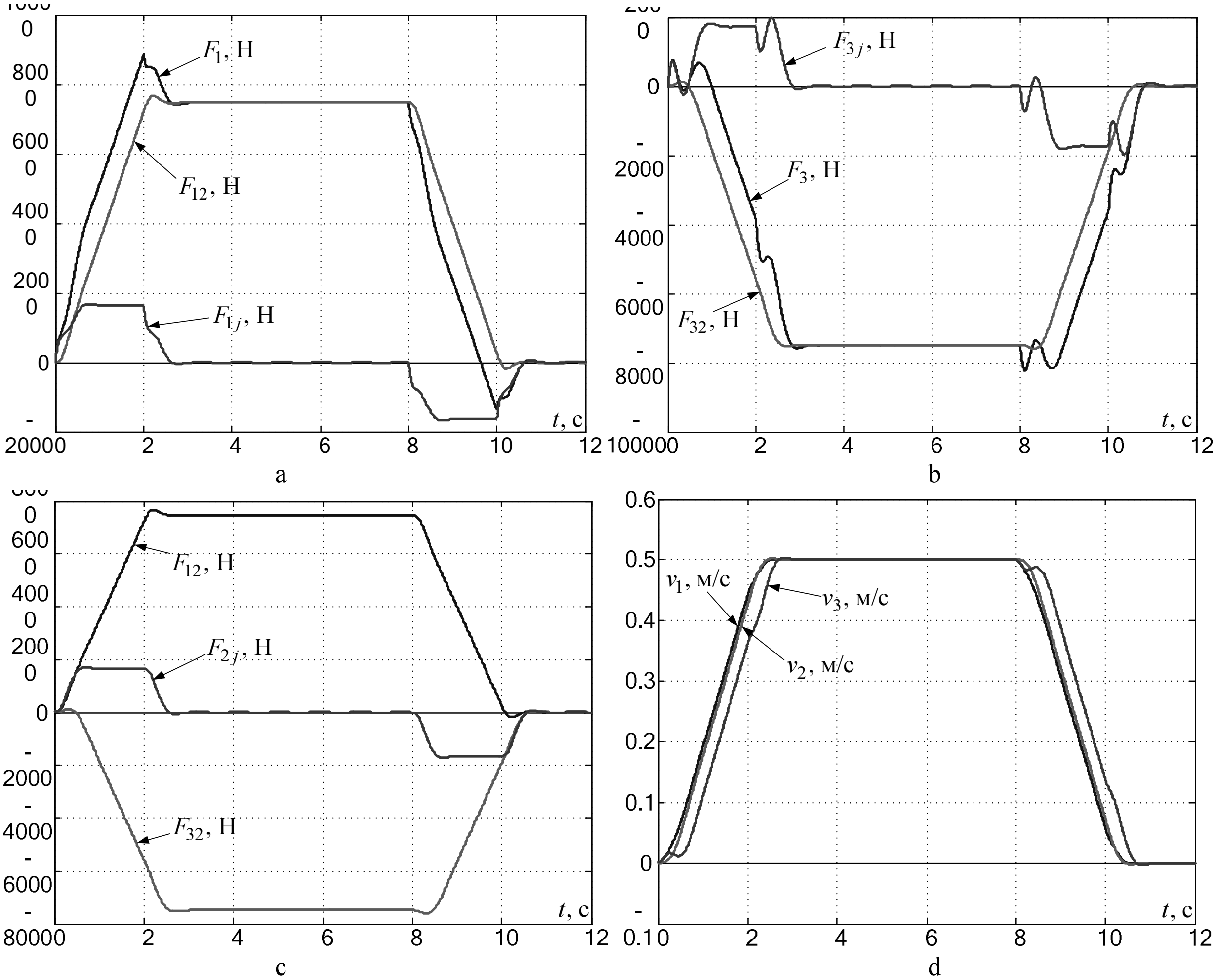

Fig. 3. Simulation results of the closed loop system with full-order state feedback controller:
a) input, elastic and dynamic forces, acting on the first mass;
b) input, elastic and dynamic force, acting on the third mass;
c) elastic forces applied to the second mass and the total dynamic force;
d) linear velocities of the lumped masses;

One of the possible reasons is the redundancy in terms of fed back signals, i.e. velocity and the elastic force acting on the right wheel pair are used to compute the input force for the left wheel pair and vice versa. A possible solution would be a design of reduced-order state space controllers for two independent two-mass systems representing the interaction between the lumped masses m_1, m_2 and the corresponding part of m_2, divided between these systems according to the trolley position. The closer the trolley is to a wheel pair, the larger part of m_2 will be included in the corresponding system.

The block diagrams of the fictitious autonomous two-mass systems are shown in Fig.4 and the overall control scheme – in Fig.5. The gain values k_{G_1} and k_{G_3} are computed so that the total closed loop system gain is unitary.

The simulation results for the case of trolley placed at l=8 m from one of the wheel pairs with the crane span L=20 m and the mean geometric root of the characteristic polynomial of $1/25T_{\text{т}} = 10$ rad/s are shown in Fig.6.

The analysis of obtained time diagram shows, that both elastic forces are equal meaning that both wheel pairs equally contribute to the crane acceleration. This also means equal distribution of elastic forces along the bridge, which reduces the mechanical strain and thus contributes to the increase of crane lifespan. By further adjusting the mean geometric root a smoother time diagram of input forces can be obtained.

Summary

1. A full-order state feedback controller is able to suppress the elastic structural vibrations of an overhead crane, but only the full elastic force transient is optimized. The motor current are held constant which leads to an increase of copper heat losses. Moreover the occurrence of severe crabbing is observed, which results in increase of mechanical stress values at specific construction nodes.

2. For the purposes of controller synthesis the second lumped mass can be divided into two pats thus resulting in substitution of a three-mass mechanical system with two autonomous two-mass systems. The distribution of m_2 between these subsystems is performed according to the current trolley position.

3. For each of the autonomous system a reduced-order state feedback controller can be designed, thus optimizing both elastic and input forces leading to effective vibrations suppression.

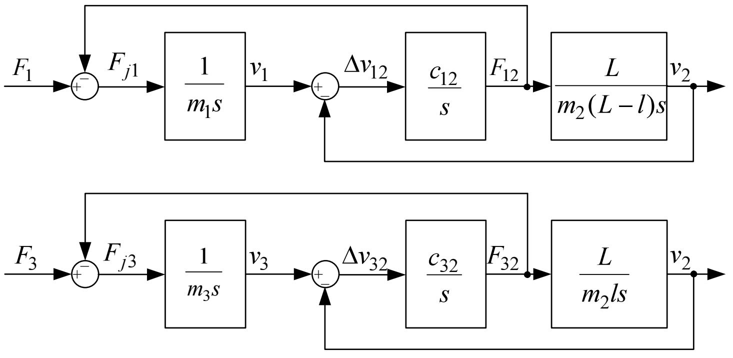

Fig. 4. Fictitious autonomous two-mass systems

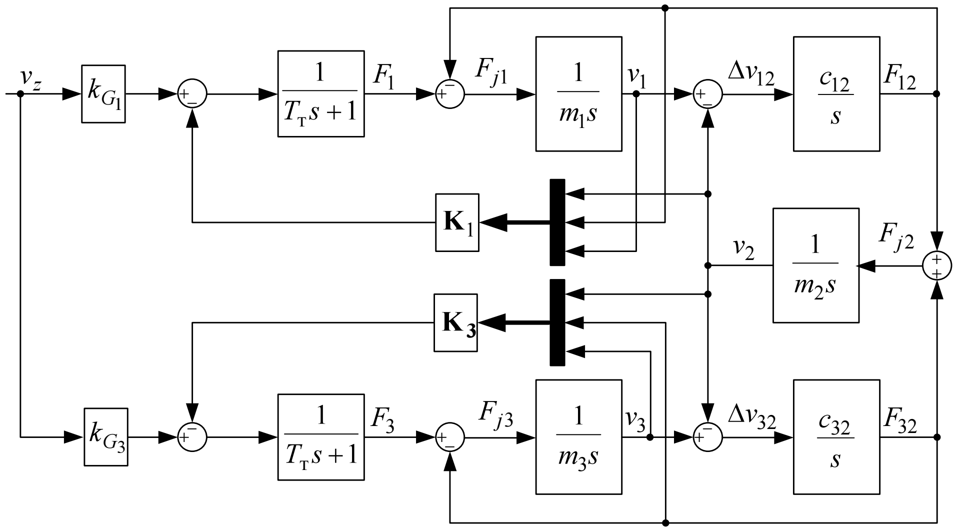

Fig. 5. Block diagram of the closed loop system with reduced-order state feedback controllers

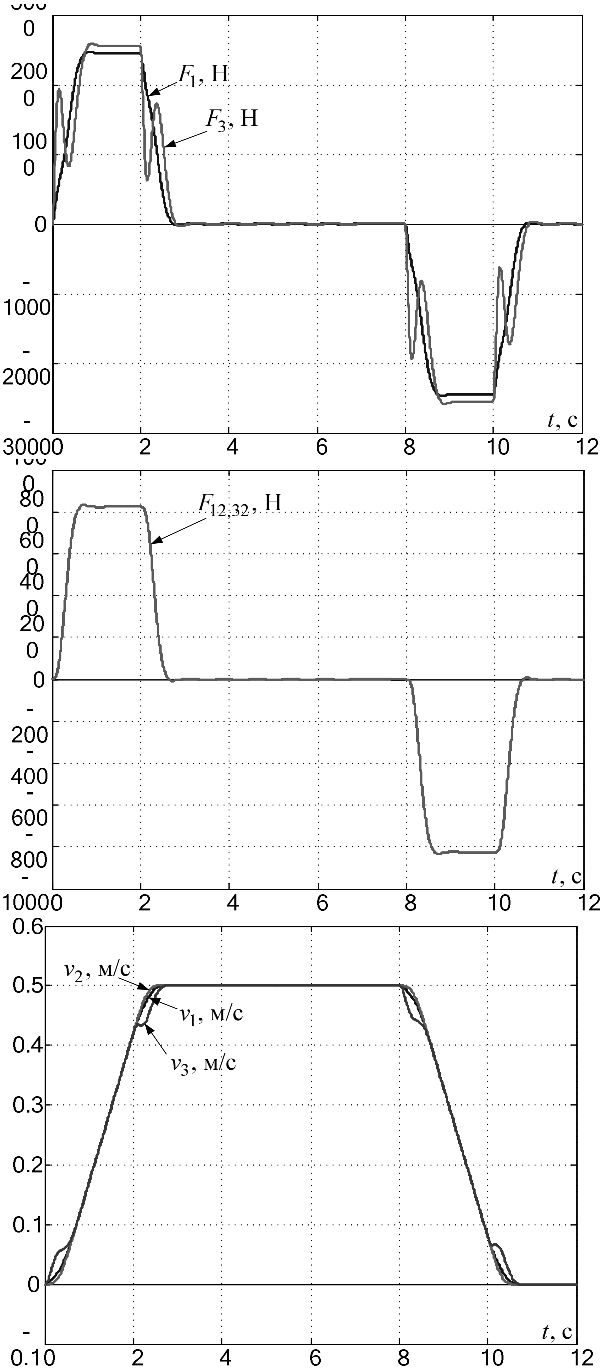

Fig. 6. Simulation results of the closed loop system with reduced-order state feedback controller

References

1. Ilharfi A., (2011), Control Design of an Overhead crane System from the Perspective of Stabilizing Undesired Oscillations, *IMA Journal of Mathematical Control and Information Publ.,* 28, pp. 267 – 278.

2. Singhose W., Porter L., Kenison M., and Kriikku E., (2000), Effects of Hoisting on the input Shaping Control of Gantry Cranes, *Control Engineering Practice Publ.,* 8, pp. 1159 – 1165.

3. Buch A., Palis F., Schwarzkopf A., and Albrecht K., (1997), Regelung Schwingungsfähiger Systeme Höherer Ordnung, *Proc. Moderne Methoden der Regelungs- und Steuerungsentwurfs,* Magdeburg, Germany, pp. 123 – 129.

4. Palis F., and Lehnert M., (1992), Motion Control of Crane Drives by Fuzzy-controller, *Proc. ED&PE 1992, International Conference on Power Electronics and Electrical Drives,* Vol. 2, CSFR, 14-16 September 1992, pp. 297 – 301.

5. Yazid E., Parman S., and Fuad K., (2011), Open-loop Responses of Flexible Gantry Crane System, *Journal of Applied Sciences Publ.,* 11 (10), pp. 1716 – 1724.

6. Pietryga U., (2011), Aktuelle Trends in der Entwicklung von Ship-to-Shore (STS) Containercrane *19. Internationale Kranfachtagung,* Magdeburg, Germany, pp. 128 – 140.

7. Recktenwald A., (2011), Aktiver Schwingungsdämpfer für Krane *19. Internationale Kranfachtagung,* Magdeburg, Germany, pp. 142 – 146.

8. Garcia-Herreros I., Kestelyn X., Gomand J., Coleman R., and Barre P.-J., (2013), Model Based Decoupling Control Method for dual Drive Gantry Stages: A case study with Experimental Validations, *Control Engineering Practice Publ.,* 21, pp. 298 – 307.

9. Tolochko O.I., Palis F., and Bazhutin D.V. Gashenie gorizontal'nykh uprugikh kolebanii konstruktsii mostovogo krana [Suppressing the Horizontal Elastic Vibrations of an Overhead Crane Structure], (2012), *Elektromekhanichni i Energozberigayuchi Sistemi. Tematichnii Vipusk "Problemi Avtomatizovanogo Elektroprivoda. Teoriya i Praktika"*, Kremenchuk, Ukraine, *Kremenchuk National University*, Vol. 3/2012 (19), pp. 336 – 339 (In Russian).

10. Palis F., Tolochko O.I., and Bazhutin D.V. Analiz poperechnykh kolebaniy mostovogo krana pri izmenenii polozheniya telezhki [Analysis of the Transverse Vibrations of the Bridge Crane with Trolley Position Changes], (2013), *Visnyk Natsional'nogo Tekhnichnogo Universytetu „Kharkivs'kyy Politekhnichnyy Instytut"*, Kharkiv, Ukraine, National Technical University „Kharkiv polytechnical Institute", Vol. 36/2013 (1009) , pp. 36 – 39 (In Russian).

11. Tolochko O., and Bazhutin D., (2013), Suppression of Horizontal Structural Vibration of Overhead Crane in Transversal Direction Given Fixed Trolley Position *Electrotechnical and Computer Systems*, Vol. 12/2013 (88), pp. 14 – 22.

Received 15.05.2015

Tolochko
Olga, D.E., professor, head of department "Electric drive and industrial installations automation", National Technical University Donetsk.
E-mail: tolochko_oi@mail.ru

Bazhutin
Denys, PhD. student at the department "Electric drive and industrial installations automation", National Technical University Donetsk.
E-mail:
denys.bazh@gmail.com