Parametric Synthesis of Fractional Order Controllers for a Two-Mass Electromechanical Fire Lift's Basket Turning System

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***Abstract* – In practice, the fire lifts arrow is a complex and not completely rigid object. Imperfect manufacturing of mechanical elements and their connections, elastic deformations of the arrow during operation, reactive action of fire-extinguishing substances cause elastic oscillations when the basket is moved. A promising method of damping elastic vibrations of the arrow is the use of an automatic control system. The synthesized ACS driven by the movement of the arrow should provide the following requirements: static and dynamic accuracy of reproduction of given trajectories, high speed, smooth acceleration and braking of the motor, the necessary margin of stability, absence of significant over-regulation in transition modes, low sensitivity to coordinate and parametric disturbances, etc. To meet these requirements, a number of fundamentally different ACSs and methods of their synthesis were analyzed. As a result of the analysis by the method of the generalized characteristic polynomial, a positional three-loop system of subordinate control by the rotation of the basket was synthesized, taking into account the elastic properties of the basket with the arrow. The synthesized system of subordinate control allows damping of elastic oscillations, providing optimal transitional processes of basket rotation and low sensitivity, in steady state, to the action of disturbances. The transition functions of the angular speed controllers of the motor and basket, which were obtained in the process of synthesis, are of a high order and turned out to be quite complex from the point of view of practical implementation. It is proposed to replace these controllers with more compact $PI^{\lambda}D^{\mu}$ controllers or fractional order controllers. Conducted research through mathematical modelling confirmed the effectiveness of replacing high-order angular speed controllers of the motor and basket with fractional-order controllers or $PI^{\lambda}D^{\mu}$-controllers, the transfer functions of which are determined by approximating the transition functions of the controllers using the genetic algorithm method.**

***Keywords* – fire lifts, platform's rotational mechanism, fractional order controller, synthesis, approximation**

I. INTRODUCTION

Various types of special fire truck ladders, both with and without baskets, and fire lifts are used for rescue operations and extinguishing fires at significant heights. The work of rescuers using such equipment is dangerous both for them and for the victims. Therefore, a number of strict requirements are put forward to lifting equipment [1].

Structurally, the basket movement system consists of the following main mechanisms: platform rotation, lifting and unfolding of knees (arrow) for articulated forklifts and basket lifting, unfolding and extending mechanisms for telescopic forklifts. All of them have their own control system and in modern forklifts are united by a common control system that has a higher hierarchical level. The quality of movement of the basket depends on the operation of all these control systems.

Since the arrow of the lifting mechanism is not completely rigid, deformations of the arrow occur. Due to elastic deformations of the arrow, imperfect manufacturing of mechanical elements and their connections, large masses of moving parts, inefficient operation of the control system itself, reactive action of fire extinguishing agents, wind load when moving the basket, elastic oscillations occur in both vertical and horizontal planes - yes called "coordinate perturbations". These factors negatively affect the operation of the system, and therefore complicate the rescuers work.

Damping of elastic oscillations with only mechanical devices is ineffective. Therefore, along with mechanical devices, a promising way of damping oscillations, and therefore of moving and stabilizing the basket in the given coordinates, provided that the task is completed, is the use of an automatic control system (ACS) [2, 3], which makes the work of rescuers safer and more efficient.

By turning the basket, the ACS should work in positioning and stabilization mode. During the rotation of the basket, parametric and coordinate perturbations are possible. Parametric perturbations include: a change in mass moments of inertia due to a change in the position of the basket; a change in the parameters of electrical equipment due to a change in environmental climatic conditions and physical "aging". Coordinate disturbances include: inefficient operation of the ACS when moving the basket, reactive effect of fire extinguishing agents, wind load.

ACS by turning the fire lift's lift basket should be minimally sensitive to all these disturbances. The ACS should be configured in such a way as to ensure the aperiodic type of the speed transition process and angle coordinates in the ideal case.

II. LITERATURE REVIEW

One of the main control coordinates is the angle of the basket rotation. However, the structure of the basket rotation ACS also includes the internal loop for controlling the speed of the executive motor output shaft and the internal loop for controlling the speed of the basket rotation. Quantitative and qualitative indicators of the basket rotation angle coordinate significantly depend on their settings.

In order to ensure the necessary indicators of the basket rotation angle coordinates, a number of fundamentally different ACSs and methods of their synthesis were analyzed. The need to ensure the smoothness of movement can be obtained under modal control [4]. During synthesizing a modal control system (MCS), an important aspect of solving the problem is the selection of desired standard characteristic polynomials. However, despite the significant advantages of such a system, it is difficult to set up and does not provide an opportunity to adjust and limit intermediate coordinates, but only the output one.

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III. PROBLEM STATEMENT

In this article, for the damping of elastic oscillations in the horizontal plane, it is proposed to synthesize a positional system of subordinate regulation (SSR) by turning the basket, taking into account the elastic properties of the arrow, which would make it possible to ensure the necessary dynamic and static characteristics of the movement of the basket under the conditions of the influence of controlling and disturbing influences on it and, thus, to increase the efficiency of rescuers in the real conditions of their work. To implement the obtained controllers for the angular speed of the motor and the SSR of basket turning, it is proposed to replace them by approximation by evolutionary methods with more compact $PI^{\lambda}D^{\mu}$-controllers or FO controllers.

To achieve a declared purpose, it is necessary to perform the following scientific tasks:

– to synthesize a system of subordinates regulation (SSR) by rotating the basket, taking into account the elastic properties of the arrow;

– to obtain controllers of the angular speed of the motor and basket rotating replace by approximation by evolutionary methods with more compact $PI^{\lambda}D^{\mu}$-controllers or fractional-order controllers.

IV. SOLVING THE PROBLEM

The process of synthesizing SSR involves a mathematical model of the control object. In this case, it is a mathematical model of the executive motor and a mathematical model of the basket rotation mechanism taking into account the elastic deformations of the arrow. In [17], in order to ensure high static and dynamic indicators, the need to replace the mechanical gear system for turning the platform of the fire lift's with an electromechanical gearless one, built on the basis of a torque motor, was substantiated. This motor provides a combination of the ability of high-precision operation at low speeds with the need to develop a large moment on the shaft and enables short-term operation of the latter even in short-circuit mode. The absence of a reducer makes it possible to significantly simplify the mechanical part of the drive, to get rid of backlash and, as a result, the occurrence of dynamic shocks during start, stop or the action of the load on the supporting-rotating mechanism, and to significantly increase the rigidity of the mechanism.

The mathematical model of the mechanism of moving the basket in the horizontal plane is built on the basis of the kinematic scheme of the two-mass system. Without taking into account the reducer, it looks like this:

$$\left.\begin{aligned}
&M_1(p)-a_1(p)\omega_1(p)-\left[M_{12}(p)-b_{12}\left(\omega_2(p)-\omega_1(p)\right)\right]=\\
&=J_1 p\omega_1(p),\\
&M_{12}(p)=\frac{C_{12}}{p}\left(\omega_1(p)-\omega_2(p)\right),\\
&M_{12}(p)+b_{12}\left(\omega_1(p)-\omega_2(p)\right)\pm F_s(p)L=J_2 p\omega_2(p),\\
&\varphi_b(p)=\frac{1}{p}\omega_2(p)
\end{aligned}\right\} \qquad (1)$$

where J_1, J_2 – total moment of inertia of the first and second masses, respectively; M_1 – moment acting from the side of the motor; F_s – horizontal component of disturbances caused by the force of the wind and the reactive force from the water jet; C_{12} – elasticity coefficient of bending deformation; b_{12} – coefficient of internal viscous friction in an elastic arrow; a_1 – coefficient of external viscous friction; ω_1 – angular speed of the motor; M_{12} – moment of elastic deformation of the arrow in the horizontal plane; ω_2 – angular speed of the basket, φ_b – angle of rotation of the basket; p – Laplace operator.

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The sum of the time constants of the pulse-width converter T_c and the electromagnetic time constant of the motor T_m ($T_\mu = T_c + T_m = 0{,}011$ s) was taken to synthesize the controllers of the angular speed of the motor, the basket and the position of the basket for a small uncompensated time constant T_μ. Taking into account the sufficiently small value of T_μ, compared to the mechanical time constants, in the further analysis, the current loop is excluded from the SSR composition. Then the transfer function of the electrical part of the drive has the form:

$$W_{el.dr}(p)=K_{el}/(T_\mu p+1). \qquad (2)$$

On the basis of the above and mathematical models of the torque valve motor and the basket rotation mechanism (1), we build a structural diagram of the positional SSR by rotating the basket, taking into account the elastic properties of the arrow (Fig. 1). The following designations are used in the figure: $W_{cp}(p)$ – TF of the basket position controller; $W_{cs1}(p)$, $W_{cs2}(p)$ – TFs of the angular speed controllers of the motor and basket, respectively; K_{s1}, K_{s2}, K_p – transmission coefficients of the speed sensors of the first mass (motor), second mass (basket) and position sensor.

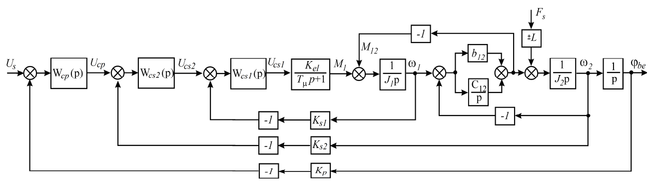

Fig. 1. Structural diagram of the positional SSR by rotating the basket, taking into account the elastic properties of the arrow

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We get the following system of equations:

$$\left.\begin{aligned} &\frac{\omega_0{}^3 J_1\left(J_2 p^2 + b_{12} p + C_{12}\right) + J_2\left(b_{12} p + C_{12}\right)}{K_p W_{cp}(p) W_{cs2}(p) W_{cs1}(p) W_{el.dr}(p)\left(b_{12} p + C_{12}\right) p} = 1, \\ &\frac{\omega_0{}^3 K_{s1}\left(J_2 p^2 + b_{12} p + C_{12}\right)}{K_p W_{cp}(p) W_{cs2}(p)\left(b_{12} p + C_{12}\right) p} = \alpha_1 \omega_0, \\ &\frac{\omega_0{}^3 K_{s2}}{K_p W_{cp}(p)} = \alpha_2 \omega_0{}^2. \end{aligned}\right\} \quad (4)$$

where ω_0 –the geometric mean root of the standard form of the characteristic polynomial, α_1, α_2, α_3 – coefficients of the selected standard form of the characteristic polynomial

After solving the system of equations (4) taking into account expression (2), we get:

(5)

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Using of fractional order controllers and, in particular, the $PI^\lambda D^\mu$ controller is an effective means of optimizing the EMS, taking into account the two-mass property of its control object and the nonlinearity of the reactive load using intelligent methods [18]

$$W_p(p) = K_p + \frac{1}{T_i s^\lambda} + T_d s^\mu, \quad (6)$$

where K_p, T_d, T_i – values of the proportional, differential, and integral components.

Let's replace the high-order angular speed controllers of the motor (CS1) and basket (CS2) with transfer functions $W_{cs1}(p)$ and $W_{cs2}(p)$ (1) with more compact $PI^\lambda D^\mu$-controllers (2) or fractional-order controllers by approximating them using evolutionary methods [18].

The procedure for approximating the EMS control object using intelligent methods, in particular particle swarm and GA, consists in comparing the time-synchronized transition process of the output coordinate of the investigated EMS $Y^*(t)$ and the transition function from the "Fractional model formation block" $Y(t)$, which corresponds to the current setting of the fractional model parameters. The discrepancy between the instantaneous values of these two functions at discrete moments of time is analyzed by the "Error estimation" block, through which the "intelligent method" of the particle swarm or GA corrects the parameters of the "Fractional model formation block" until the specified discrepancy error is reached. "Block of formation of the fractional model" upon achieving the desired accuracy fixes the parameters of the fractional model that approximates the given transition function.

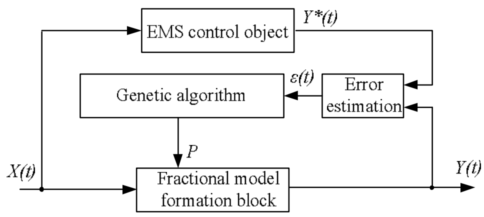

Fig. 2. Functional scheme of the approximation procedure of the high-order integer TF by fractional models using intelligent methods

To check the degree of adequacy of the replacement of the classic high-order controller CS1 with the transfer function $W_{cs1}(p)$ (1) by the $PI^\lambda D^\mu$-controller (6), a structural diagram was implemented in the MATLAB for simulation modelling. The replacement of the high-order regulator CS1 with the TF (5) 1 $W_{cs1}(p)$ (1) was carried out using the software developed for the approximation of classical parts with high-order transfer functions by fractional-order parts using the GA method according to their transition functions [19]. The GA method is implemented using the Optimization Toolbox package.

The search for the parameters of the $PI^\lambda D^\mu$-controller was carried out within the limits given in the Table 1.

TABLE I. *LIMITS OF CHANGES OF $PI^\lambda D^M$ -CONROLLER PARAMETERS*

Parameter	*Kp*	*Ki = 1/Ti*	λ	*Td*	μ
Limits	[1, 50]	[0, 100]	[0, 0,999]	[0, 100]	[0, 0,999]

As a result, the following TF of the $PI^\lambda D^\mu$ – controller for motor angular speed was obtained:

$$W_{cs1}{}'(p) = 12{,}197 + 12{,}241 p^{-0{,}185} + 2{,}434 p^{0{,}957}. \quad (7)$$

In fig. 4 shows the transitional functions of the CS1 controller with the TF $W_{cs1}(p)$ (5) (curve 1) and the $PI^\lambda D^\mu$-controller with the TF $W_{cs1}{}'(p)$ (7) (curve 2) obtained by using GA.

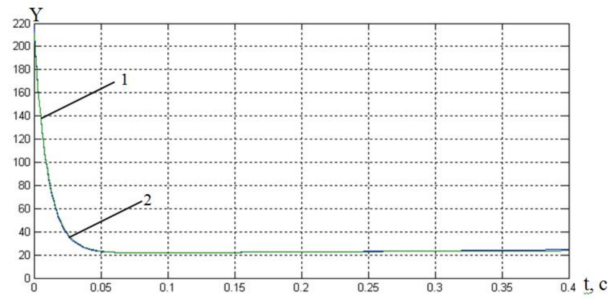

Fig. 3. Transition functions of the motor angular speed controller: curve 1 – with TF (5), curve 2 – with TF (7)

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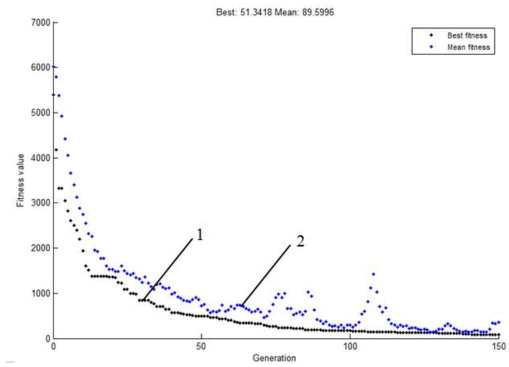

Fig. 4. Approximation process during the synthesis of $PI^\lambda D^\mu$-controller parameters using GA

The conducted studies confirm the effectiveness of replacing the high-order regulator CS1 with the TF $W_{cs1}(p)$ (5) by the $PI^\lambda D^\mu$-controller (7), the TF of which is determined by approximating the transition function of the controller from the transfer function (6) by the GA method.

In [19, 20], it is proposed to approximate the high-order transfer function using a FO TF with a zero and a pole:

$$W(p) = k\frac{b_1 p^{\beta_1}+1}{a_1 p^{\alpha_1}+1}. \qquad (9)$$

Adapting the structural diagram of fig. 5 to the TF (9) and using the Optimization Toolbox optimization package for synthesis by the GA method and setting the reference transient process that corresponds to the CS2 part (5), we will synthesize the fractional controller (9) by the GA method. The population size is 100 by default. As a result, the following TF of the fractional controller was obtained:

. (10)

In fig. 7 shows the transition functions of the CS2 controllers with the TF $W_{cs2}(p)$ (5) (curve 1) and the one obtained using the GA with the TF (10) (curve 2).

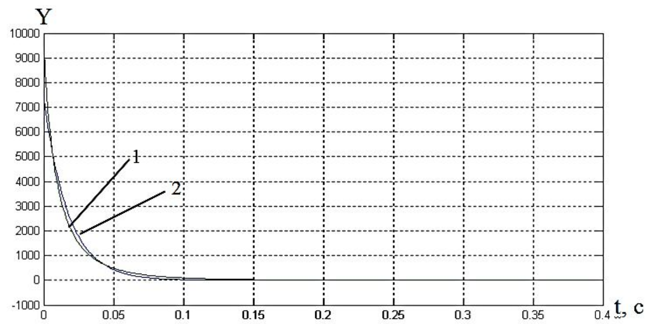

Fig. 5. Transition functions of the basket angular speed controller: curve 1 – with TF (5), curve 2 – with TF (10)

The obtained research results confirm the effectiveness of replacing high-order controllers CS1 and CS2 with TFs $W_{cs1}(p)$, $W_{cs2}(p)$ (5) with $PI^{\lambda}D^{\mu}$-controllers or fractional-order controllers, whose transfer functions are $W_{cs1}'(p)$ (7), $W_{cs2}'(p)$ (8), $W_{cs1}^{o}(p)$ (10) are determined by approximating the transition function of the controller from the transfer function (2) and (5) by the GA method.

V. Conclusions

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