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PLC implementation of fractional PI controller in positioning of electrohydraulic servodrive

by

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Abstract: The article describes the implementation of fractional order PI controller with the Programmable Logic Controller (PLC). The control system proposed is used for positioning of an electrohydraulic drive with Bosch Rexroth servo valve. The controller is based on PLC, working under real time operating system Automation Runtime. User interface is equipped with the touch panel of Power Panel 500 type. In the first part of the paper the fractional order calculus theory is introduced. In addition, some examples of fractional controller implementations in different kinds of objects are presented. The subsequent section focuses on author's own research. The Oustaloup's method description is recalled along with its computer implementation. Further, the impact of finite order of the approximation function is verified. The article includes the description of test stand structure, code generation and implementation of PI controller on the dedicated PLC.

Keywords: fractional order controller, electrohydraulic drive, electrohydraulic servovalve, fractional order calculus

1. Introduction

The traditional PID controller is currently the most widely used form of feedback controller in industrial applications. This is also the most common type of controller used in electrohydraulic drives. Notwithstanding this popularity, it remains an important issue how to find the new way of regulation, providing better dynamics and positioning accuracy. The last few years have seen the increasing amount of work, related to the application of the fractional order controllers in different areas of engineering. The present article focuses on fractional order PI implementation on the programable logic controller (PLC) for electrohydraulic drive positioning.

1.1. Literature overview

In the last few years a lot of researchers have been focusing on applications of fractional calculus in various areas of physics and engineering.

Faieghi and Nemati (2011) concentrate on basic relations in the fractional calculus and their implementation in Matlab Simulink software. The article presents the definition, approximation method and rational order controller structure. The paper also proposes the methods for selection of regulator parameters, confirmed by simulations performed in Matlab Simulink environment.

Djouambi et al. (2007) described the optimal approximation of the fundamental linear fractional order transfer function, using a distribution of the relaxation time function. The optimal parameters of the approximated model are derived by the authors mentioned through minimizing simultaneously the gain and the phase error between the irrational transfer function and its rational approximation. As the example for the approach a simple analogue electronic circuit was used.

Zamani et al. (2009) described the use of the fractional order calculus for designing control with automatic voltage regulator. The authors referred to used the particle swarm optimization algorithm to prepare the aforementioned design procedure. The data, collected from the FOPID (fractional order PID) were compared with the functioning of the traditional PID controller. The comparison has shown that the fractional PID controller, proposed by Zamani et al. (2009) can importantly improve system robustness with respect to model uncertainties.

Oprzedkiewicz and Kolacz (2016) proposed a new approach to building of non integer order models for speed control in AC motors. The models have the form of hybrid transfer functions containing the integer order and the fractional order parts. The parameters of the respective models were identified with the use of the least square method. The obtained models were compared to integer order transfer model with delay identified.

Vinagre et al. (2007) described the methods for fractional order PID controller design and auto-tuning. The auto-tuning method is performed with the use of relay feedback in order to characterize some points of the frequency response of the plant and frequency domain specifications for tuning the fractional controller. The same authors presented, as well, the software and hardware strategies for efficient implementation of controllers in industrial applications. As the example, these authors used a model prepared in Matlab Simulink software.

On the other hand, there are implementations of various types of control regarding the electrohydraulic servo drive. Thus, Milecki et al. (2014) describe the implementation of the Model Following Control method in electrohydraulic servo drive. In this study, the drive was equipped with a new type of proportional valve with synchronous motor (see Milecki and Rybarczyk, 2015). The test was performed with the use of the step response signal. This method required building of the model of the considered object, and therefore the article included equations, describing the functioning of the drive and the valve.

The main subject of the article by Deticek and Zuperl (2011) was the application of a closed loop control system for position control of electrohydraulic servo drive. The study was carried out with the use of theory of adaptive feedback systems. The proposed new control structure is based on three main parts, which are precisely described in the article referred to. Of essential importance for the author of the present article was the basic equation, describing the electrohydraulic drive. The effectiveness of the approach proposed was proven by laboratory experimental tests.

The monograph by Kaczorek (2009) focuses on the mathematical formulae and the theory behind the fractional order systems, and this provides the foundations for more application-oriented studies of the subject.

Chen et al. (2009) provided a detailed description of the numerical methods for simulating fractional order systems and the respective discretisation methods are given in detail. At the end of the paper, the authors present some analog and digital representations of the system considered.

One of the most popular libraries, which are used for modelling of fractional system was prepared by Tepljakov (2012). He implemented tools, which can be used for simulating the fractional controller and for modelling of different types of fractional systems. The toolbox consist of the following modules: main module for fractional system analysis, identification module for system identification in time and frequency domains, control module for fractional PID design, tuning and optimization tools. A similar library was elaborated by Valerio and Sa da Costa (2005), but it has not been further developed.

2. The control system considered

2.1. Hydraulic part description

The here described and considered electrohydraulic servodrive is based on the hydraulic cylinder and servo valve (Fig. 1). The stroke of the cylinder is $x =$ 20 mm. In this servodrive, the author used non-zinc hydraulic oil with high viscosity index, of the type of Draco HV 46 Premium Oil. The hydraulic power supplier has the following parameters: power of 37 kW, maximum flow rate of 100 dm^3/min, maximum pressure of $p_0 = 40$ MPa, filtration at 6 microns. The servovalve type 4WS2EM10-45, used in the here presented and further considered control setup is produced by Bosch Rexroth company.

2.2. Electrical structure

The control system (Fig. 2) is based on PLC working under real time operating system Automation runtime with touch panel type Power Panel 500 (see B&R Automation, 2016).

The input and output modules are connected via Powerlink interface bus X20BC0083. This Powerlink interface provides the transmission speed of 100 Mbit/s and a synchronization accuracy of +/- 100 ns. Therefore, it is sufficiently

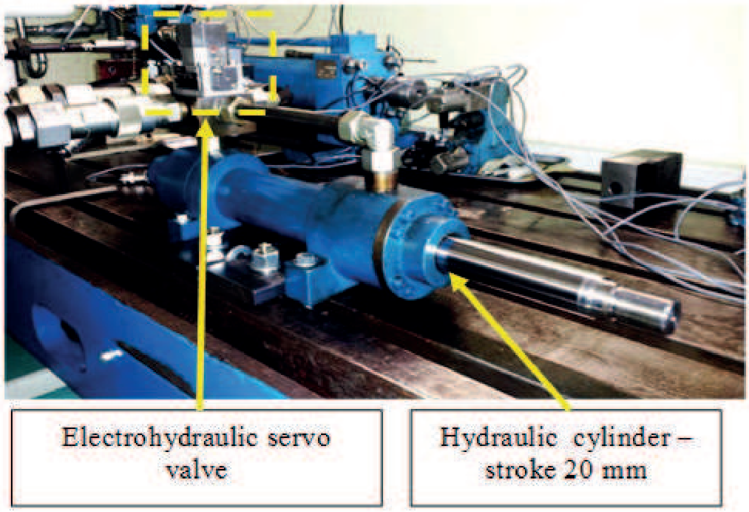

Figure 1. View of the electrohydraulic drive

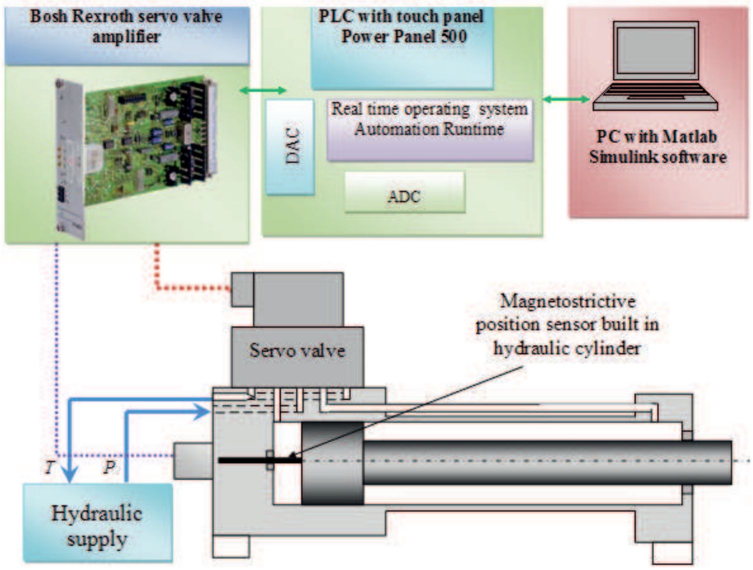

Figure 2. The scheme of the control system

accurate for the most demanding tasks like, for example, positioning. The control system is also equipped with analog input module X20AI4632 connected to the magnetostrictive sensor built in the hydraulic cylinder. The analog output module of type X20AO2632 was connected to the servovalve amplifier (Fig. 3).

Due to the high level of noise from the pump, the position control and the measurement have been placed in the outer room (see Figs. 4, 5).

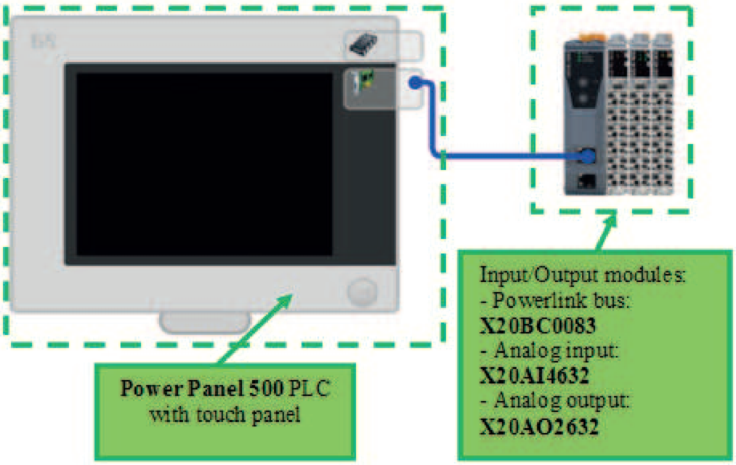

Figure 3. View of the PLC structure taken from B&R System Designer

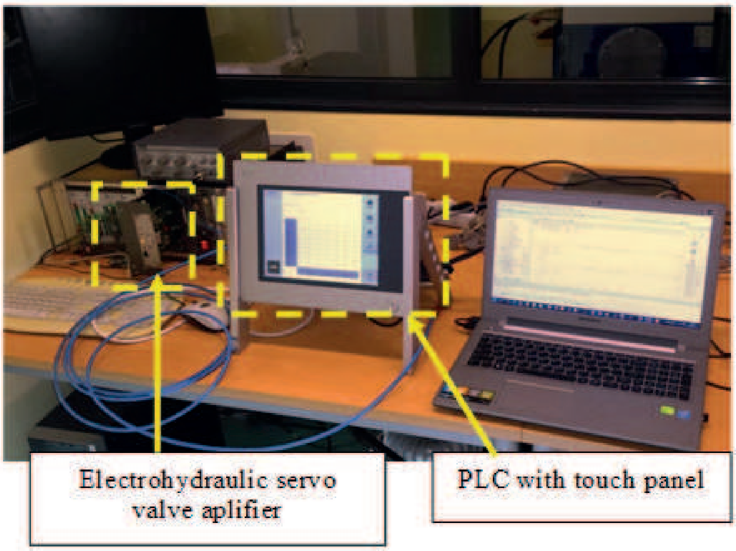

Figure 4. View of the control stand in the laboratory

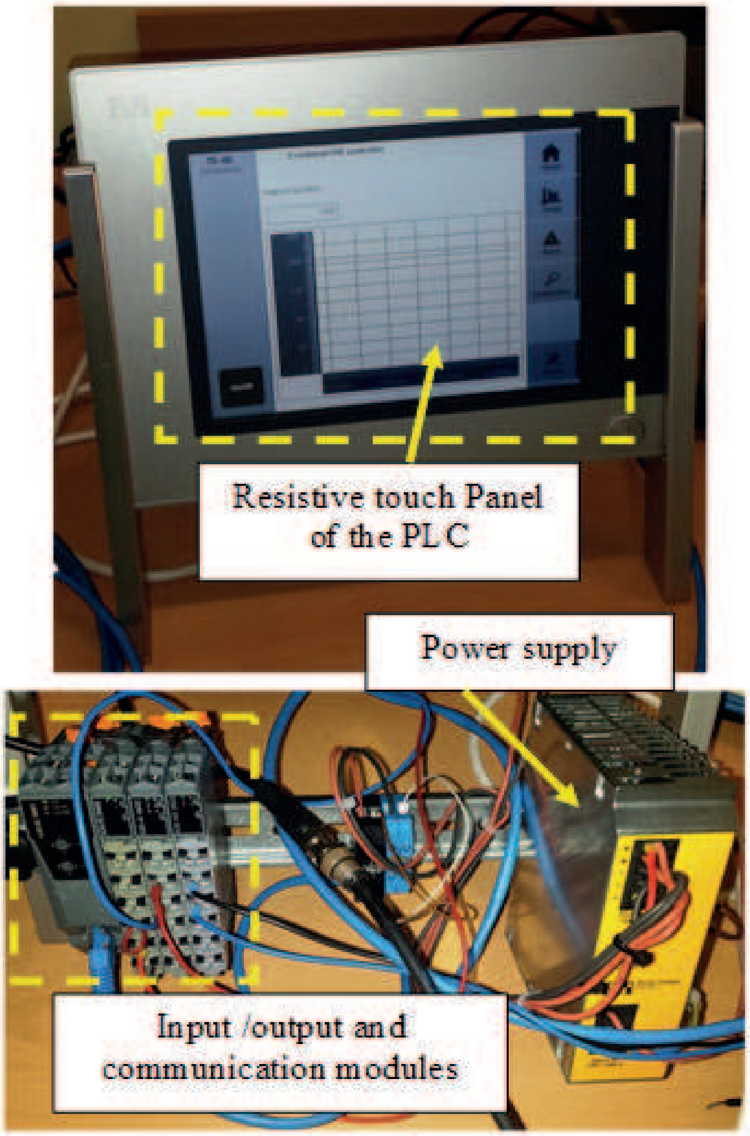

Figure 5. View of the PLC controller

2.3. PLC code

The control program is written in Structured Text and ANSI C languages. The task, responsible for the fractional order controller, worked with the time base of 0.4 ms. The task is placed on the PLC taksclass divider (Fig. 6), with tolerance equal to 0, in order to implement the hard real time operating system idea.

A visualization was performed with steps of 12 ms, in order to not charge the CPU (Central Processing Unit) of PLC (Fig. 7). The visualization includes the basic parameters of the controller, like: the actual and the setpoint positions of the hydraulic piston, the setpoint position of the servovalve spool, the type of controller (P, PI, fractional PI). The author added to these parameters also diagnostic functions and the alarm page.

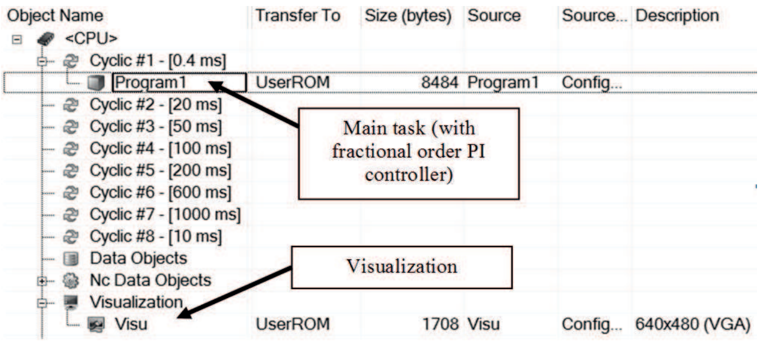

Figure 6. The screen from the CPU taskclass divider

2.4. Approximation of fractional order equations – PLC implementation

The method of Oustaloup (see, e.g. Oustaloup, 1983) was used by the present author for approximation of the fractional order controller (needed for software implementation). An explanation of this method requires recalling of the definition of fractional order calculus. The fractional differential-integral equation can be described by the following equations (B&R Automation, 2016):

$$
{}_aD_t^\alpha = \begin{cases} \frac{d^\alpha}{dt^a} & \Re(\alpha) > 0 \\ 1 & \Re(\alpha) = 0 \\ \int_\alpha^t (dr)^{-\alpha} & \Re(\alpha) < 0 \end{cases} \tag{1}
$$

For practical calculation of results of the action of this operator various definitions are being used (Riemann-Liouville, Caputo, Grünwald-Letnikov). The Laplace operator of fractional differentiation for zero initial conditions is described by the formula (see Faieghi and Nemati, 2011):

$$
L[{}_aD_t^\alpha f(t)] = s^\alpha F(s). \tag{2}
$$

The present author used the approximation method, following Oustaloup, described by the following formula:

$$
s^q = k \prod_{n=1}^{N} \frac{1 + \frac{s}{\omega_{zn}}}{1 + \frac{s}{\omega_{pn}}} q>0 \tag{3}
$$

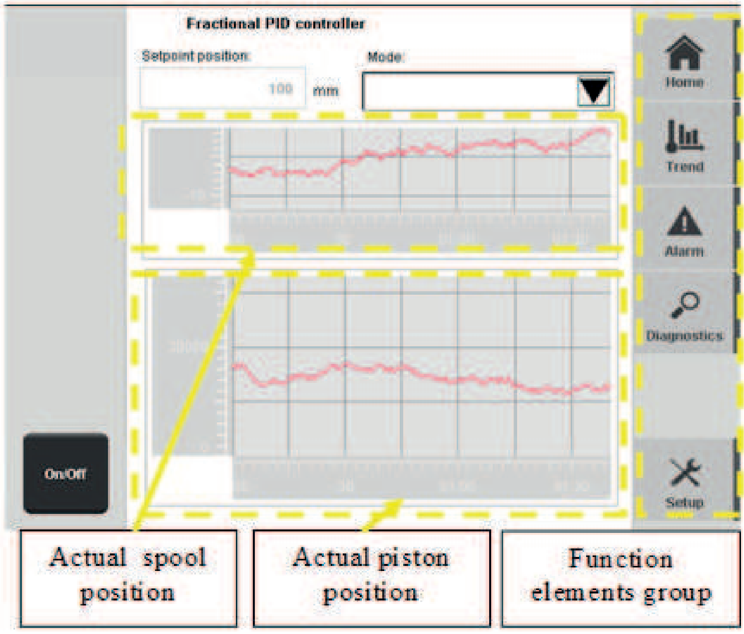

Figure 7. Visualization

where:

$$a = \left(\frac{\omega_h}{\omega_1}\right)^{\frac{q}{N}} \tag{4}$$

$$\eta = \left(\frac{\omega_h}{\omega_1}\right)^{\frac{1-q}{N}} \tag{5}$$

$$\omega_{z1} = \omega_1\sqrt{\eta} \tag{6}$$

$\omega_{zn} = \omega_{z,n-1}\eta$ n=2,..,N (7)

$\omega_{pn} = \omega_{z,n-1}a$ n=2,..,N (8)

with:

k – gain adjusted so that both sides of (3) have unit gains at 1 rad/s (see Valeria and Sa da Costa, 2005),

q - the fractional order (real number),

N - order of the finite TF approximation for both,

ω_1 - lower frequency limit,

ω_h - upper frequency limit.

The continuous transfer function, taken from the Oustaloup calculations, undergo the process of discretization that can be directly implemented on the PLC.

Approximation of the fractional order integrator for $s^{0.9}$ for N = 1 is as follows:

$$s^{0.9} = \frac{0.005623s^3 + 4.744s^2 + 84.36\,s + 31.62}{s^3 + 26.68s^2 + 15s + 0.1778} \tag{7}$$

Approximation of the fractional order integrator for $s^{0.1}$ for $N = 1$ is as follows:

$$s^{0.1} = \frac{0.5623s^3 + 102.2s^2 + 391.6s + 31.62}{s^3 + 123.8s^2 + 323.2s + 17.78} \tag{8}$$

Approximation of the fractional order integrator for N = 5 is given as:

$$\begin{aligned} s^{0.1} = {} & \frac{0.5623s^{11} + 541.1s^{10} + 1.353e05s^9 + 1.089e07s^8}{s^{11} + 866.6s^{10} + 1.952e05s^9 + 1.414e07s^8} \\ & \frac{+\ 2.987e08s^7 + 2.848e09s^6 + 9.49e09s^5 + 1.105e10s^4}{+\ 3.495e08s^7 + 3.001e09s^6 + 9.006e09s^5 + 9.446e09s^4} \\ & \frac{+4.472e09s^3 + 6.172e08s^2 + 2.741e07s + 3.162e05}{+3.442e09s^3 + 4.279e08s^2 + 1.711e07s + 1.778e05} \end{aligned} \tag{9}$$

Upscaling the order of the finite TF approximation gives a much more complicated approximated continuous equation. Because of limited computing power of CPU, it is important to implement on PLC the equation with a not expanded polynomial. Valerio and Sa da Costa (2005) proved that increasing the order of the finite TF value N does not significantly affect the final result (but causes the appearance of a ripple in both gain and phase behaviour). The chart, showing the influence of order increase of the finite TF value for the model obtained is provided in Fig. 9.

3. Experimental investigations

The aim of experimental investigations was to show the influence of changes in the fractional denominator of integrator in PI controller for electrohydraulic servodrive positioning (Fig. 10).

The controller, implemented on PLC (Fig. 11) is described by the following formula:

$$G_{FOPI}(s) = k_p + k_i \cdot \frac{1}{s^q}. \tag{10}$$

The experimental test has been performed for the step response with the following parameters: $k_p = 250$, $k_i = 100$, $p_0 = 10$ MPa (Fig. 12) and $k_p = 250$, $k_i = 30$, $p_0 = 10$ MPa (Fig. 15). The setpoint position is set to 150 mm. The movement is started from the central position of the hydraulic drive, because of stiffness transition in the entire length of the hydraulic cylinder. This phenomenon is associated with the liquid compressibility.

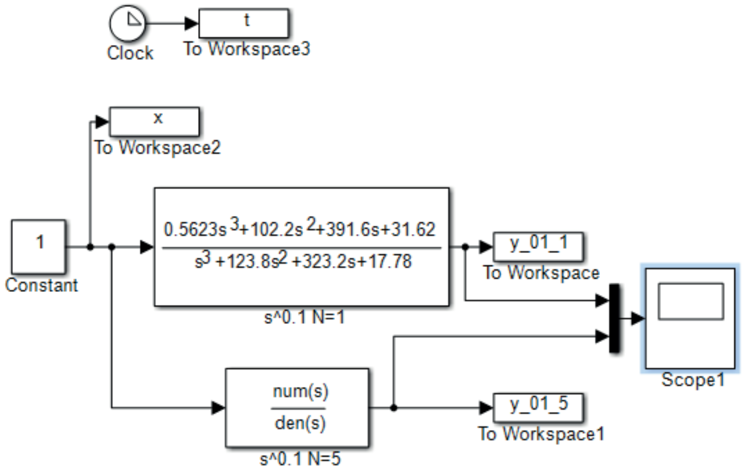

Figure 8. Testing of different approximations of s0.1 in Matlab Simulink software

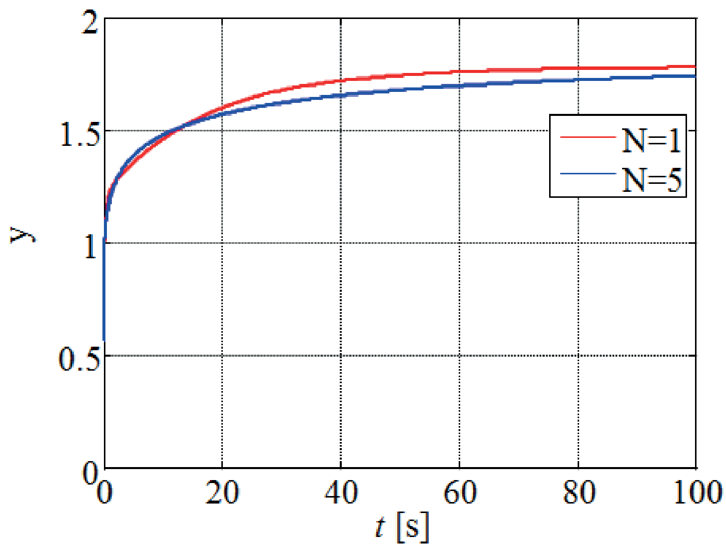

Figure 9. Approximation of the fractional integrator for different values of N

The use of fractional order formula in PLC required an approximation method to be used. Approximation of the fractional order integrator for $1/s^{0.9}$ can be described by the following equation:

$$G_{FOPI}(s) = k_p + k_i \cdot \frac{0.005623s^3 + 4.744s^2 + 84.36\ s + 31.62}{s^3 + 26.68s^2 + 15s + 0.1778}\ . \quad (11)$$

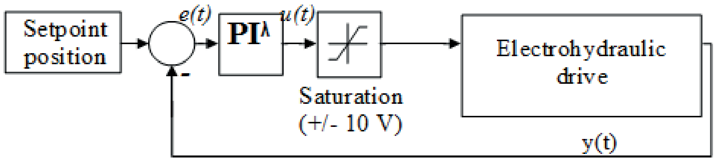

Figure 10. PI controller scheme

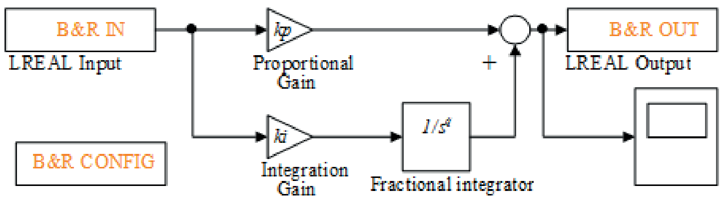

Figure 11. Fractional PI controller implemented in Automation Target for Simulink (see B&R Automation, 2016)

Approximation of the fractional order integrator for PI controller with $1/s^{0.1}$ is given by:

$$G_{FOPI}(s) = k_p + k_i \cdot \frac{0.5623s^3 + 102.2s^2 + 391.6s + 31.62}{s^3 + 123.8s^2 + 323.2s + 17.78}. \tag{12}$$

The next step consists in discretization of the continuous time transfer function with the use of Z-transformation. The discrete form of the fractional PI with $1/s^{0.9}$ looks as follows:

$$G_{FOPI}(s) = k_p + \\ +k_i \frac{0.005623\ z^3 + 0.001779\ z^2 - 0.01915\ z + 0.01175}{z^3 - 2.899\ z^2 + 2.797\ z - 0.8988} \tag{13}$$

The discrete form of the fractional PI with $1/s^{0.1}$ is given by:

$$G_{FOPI}(s) = k_p + k_i \cdot \frac{0.5623\ z^3 - 1.361\ z^2 + 1.04\ z - 0.2412}{z^3 + 123.8\ z^2 + 323.2\ z + 17.78}. \tag{14}$$

The discretization is performed for the time base equal to 0.004 s. After the discretization process the formulas were implemented directly on PLC with the use of C language.

The graphs, shown in Figs. 13, 14, 16 show the displacement of the electrohydraulic drive, correlated with control signal provided from the PLC and applied to the servovalve amplifier.

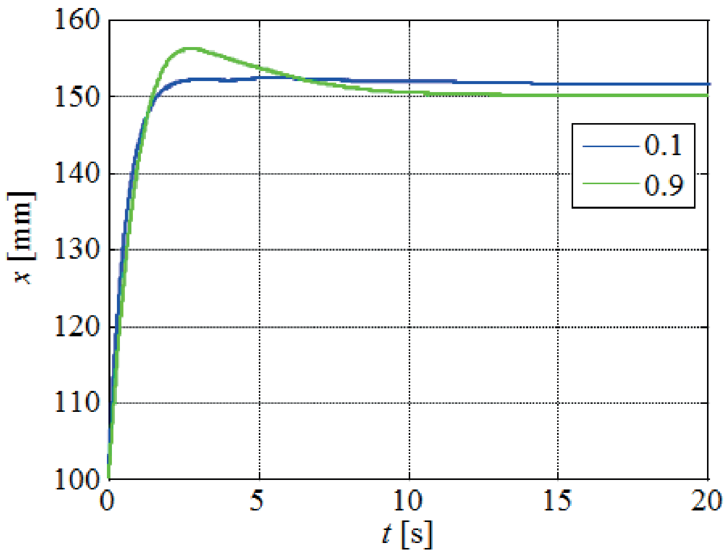

Figure 12. Step response for $k_p = 250$, $k_i = 100$, $p_0 = 10$ MPa – piston position

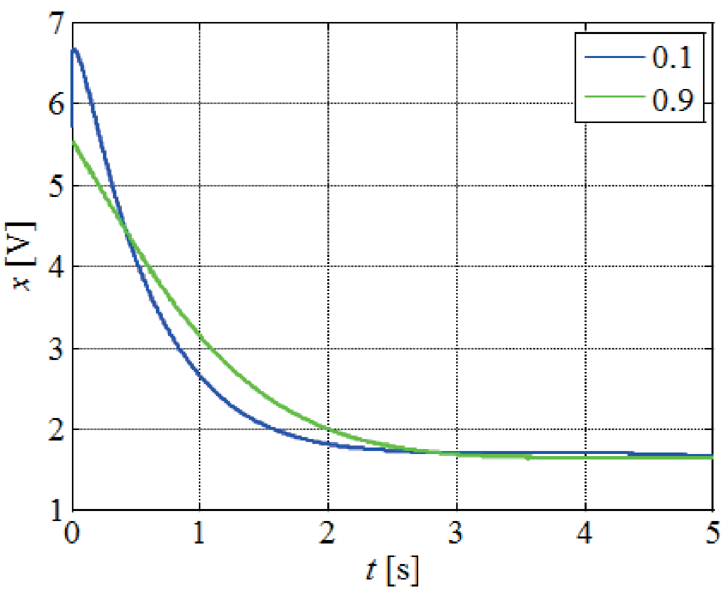

Figure 13. Step response for $k_p = 250$, $k_i = 100$, $p_0 = 10$ MPa – voltage given on servovalve control card (magnified in order to better illustrate the issue)

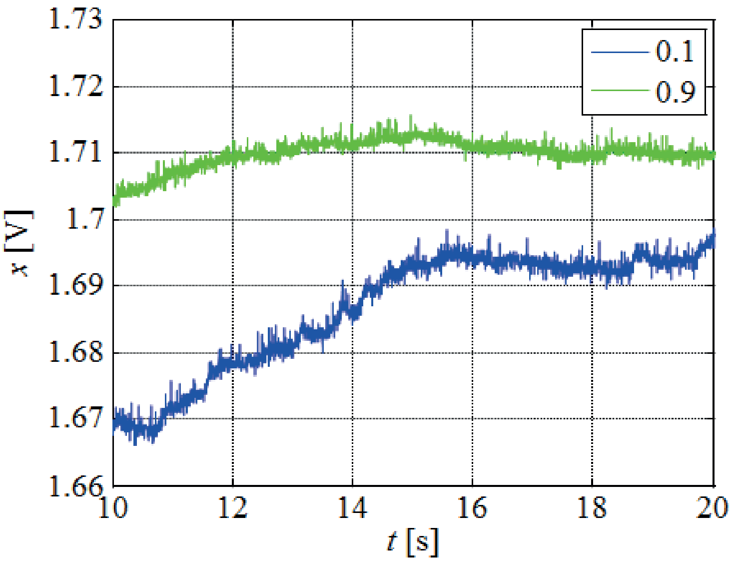

Figure 14. Step response for $k_p = 250$, $k_i = 100$, $p_0 = 10$ MPa – voltage given on servovalve control card (magnified in order to better illustrate the issue)

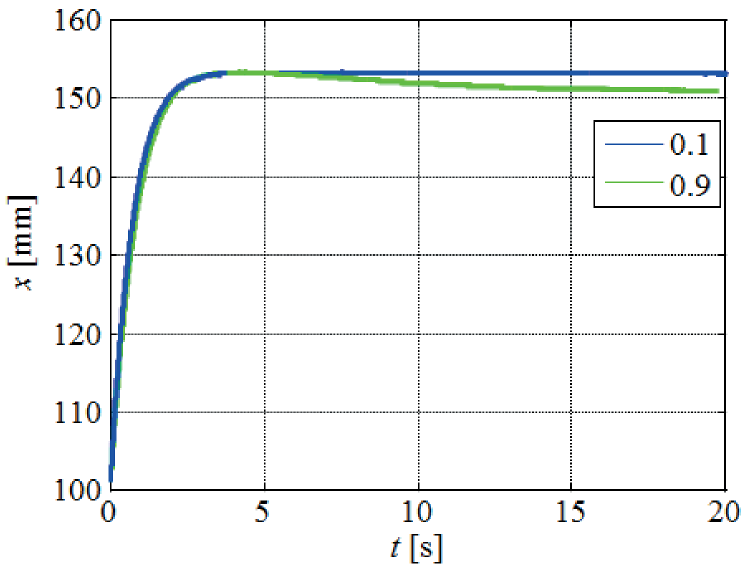

Figure 15. Step response for $k_p = 250$, $k_i = 30$, $p_0 = 10$ MPa – piston position

The data collected from the experiments were compared with the use of the

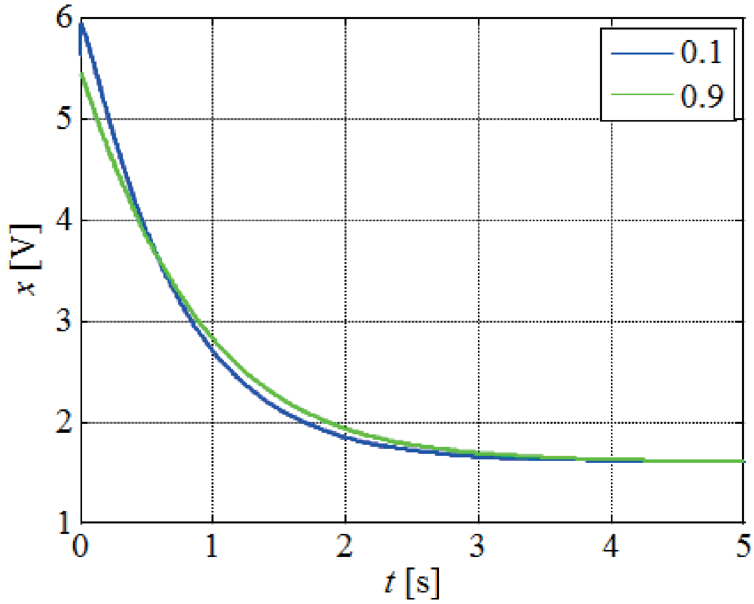

Figure 16. Step response for $k_p = 250$, $k_i = 30$, $p_0 = 10$ MPa – voltage given on servovalve control card (zooming in order to better illustrate the problem)

Integral Absolute Error method:

$$I_m = \int_0^\infty |e(t)|dt \tag{15}$$

where:

I_m - IAE – Integral Absolute Error, e(t) – control error.

Table 1. Integral absolute error

Integral Absolute Error values obtained			
k_p	k_i	q	IAE
250	100	0.1	57.78
250	**100**	**0.9**	**55.17**
250	30	0.1	84.95
250	30	0.9	65.49

The respective results of calculations are presented in Table 1. It can be seen from this table that a better quality of regulator is achieved with $k_i = 100$ and the fraction order of integrator equal to $q = 0.9$.

4. Summary

The article describes the implementation of a fractional order PI controller on the PLC. The controller was used for positioning of an electrohydraulic drive with Bosch Rexroth servo valve.

The hardware implementation of the described regulator requires a PLC with a sufficiently large computational power. The task responsible for the fractional order controller, in the proposed control system, worked with the time base of 0.4 ms. Because of PLC implementation issue, it is necessary to perform approximation of the fractional order controller. The author used the approximation method due to A. Oustaloup. Because of the limited computing power of CPU, it is important to implement on PLC the equations with a not expanded polynomial. Therefore, the order of the finite TF approximation should have low values, so that the approximation applied is involves simpler calculations.

The here described control system was tested with the use of fractional PI controller. The graphs obtained from the experiments show the best regulation results for the following parameters: $k_p = 250$, $k_i = 100$, and the integral fraction order $q = 0.9$.

The tests performed provide a starting point for further comprehensive research on the control and modelling with the use of fractional differential equations in electrohydraulic servodrives. The present author especially wishes to focus on implementation of a complex PID controller and on development of the optimal method for tuning of the fractional order controller in electrohydraulic servodrives.

Acknowledgement

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