Use of the fractional order PD controller in electro-hydraulic drive

Dominik Rybarczyk
Politechnika Poznańska, Wydział Budowy Maszyn i Zarządzania, Instytut Technologii Mechanicznej, ul. Piotrowo 3, 60-965 Poznań

Abstract: This paper presents initial research on use of the fractional order PD controller of the electro-hydraulic drive – step response in open and close loop. Test stand built based on hydraulic cylinder combined with electro-hydraulic servo valve. Control system based on PLC with touch panel. Experimental investigation is performed for different coefficient of fractional PD regulator. The aim was to check power of s denominator changes impact in PD controller. Performed test stand allowed to conduct further comprehensive investigations use of the fractional order controller in electro-hydraulic drives.

Keywords: fractional order controller, electro-hydraulic drive, servo valve

1. Introduction

The classic differential calculus assumes that the order of the differential equation (the highest derivative) is a natural number. The first discussion of whether it is possible to put real numbers in the order of the differential equation already appeared in 1695. Leibnitz noted that many physical phenomena can be described with the use of this type of equations. However, only a few years there is a possibility of an effective direct use in the control due to the increase in computing power of modern computers.

The literature review, described in below chapter (2.1), showed a lack of publications regarding the use of the fractional controllers in electro-hydraulic drives. The idea behind this article to realize initial research focus on implementation of fractional order calculus in area of electro-hydraulic servo drive control, by buildup new laboratory test stand and performer initial tests.

2. Fractional order calculus – theory

2.1 Literature overview

A lot of investigations related to the electro-hydraulic drives have been focused on improvement of the properties of these drives, by implementation of new types of control [1, 2]. Article [1] presented basis information about hydraulic system and drives. Authors described basic technics of control, applications and equipment like types of valves and cylinders.

Autor korespondujący:
Dominik Rybarczyk, dominik.rybarczyk@put.poznan.pl

Artykuł recenzowany
nadesłany 31.05.2016 r., przyjęty do druku 28.03.2017 r.

In article [3] authors focus on application of fractional order system models. They showed two examples: first one is the ultra-capacitor, where fractional order models turn out to be more precise in the wider range of frequencies than other typical used models, and the second one concerning on the beam heating problem, where again the fractional order model allows to obtain better modelling accuracy. The simulation were compared with experimental results.

In article [4] servo valve and proportional pressure valve are used to control the composite hydraulic cylinder to generate alternating force and fixed force respectively. The models of the electro-hydraulic system are built and its dynamic characteristic is analyzed based on the simulations. Simulation and experimental results have shown that the fractional order controller is effective.

In the studies [5, 6], few methods of tuning fractional order PID controller was proposed. In article [7] author used the library FOMCON implemented in MATLAB/Simulink. It has been designed by Aleksei Tepljakov from University in Tallinn. The library allows to create the models described by fractional order differential equations and build based on it models. Similar libraries was prepared by author of following publication [8], but it is not as extensive as the first of the listed.

The paper [9] includes studies of: tuning of PID controllers using fractional calculus concepts, heat diffusion, and circuit synthesis using evolutionary algorithms, fractional control of a hexapod robot, and fractional dynamics in the trajectory control of redundant manipulators.

The article [10] describes modelling of electro-hydraulic drive. In the drive a new type of proportional valve with a synchronous motor controlled by dedicated power electronics is used. The model of the electro-hydraulic drive prepared in MATLAB/Simulink is described. The study included the examination of the basic characteristics such as step response. The aim of this article was to prepare basis for further research concerning of implementation of new kind of control method in electro-hydraulic drives.

Article [11] described new accuracy estimation method for Oustaloup approximation. Oustaloup approximation is a typical and most common use to describe fractional-order systems. The accuracy of approximation can be estimated via comparison of impulse responses for object and Oustaloup approximation. The impulse response of the object was calculated with the use of an accurate analytical formula. Approach presented in the paper can be applied to effective tuning of Oustaloup approximant for some kind of application. Author of [12] showed theory behind fractional order calculus. Publication focus on the mathematical issue like: definition of *n*-order difference or fractional system with delays.

2.2. Fractional order controller basis

Fractional differential-integral equation can be described by the following of equations [5]:

$$ {}_aD_t^{\alpha} = \begin{cases} \dfrac{d^{\alpha}}{dt^{\alpha}} & \Re(\alpha) > 0 \\ 1 & \Re(\alpha) = 0 \\ \int_a^t (dr)^{-\alpha} & \Re(\alpha) < 0 \end{cases} \quad (1) $$

where a and t are the limits of the operation and α is an order.

For practical calculation results of the action the operator uses the various definitions such as the Riemann-Liouville, Caputo, Grünwald-Letnikov. A model describing the transformation of the Laplace operator of fractional differentiation row for zero initial conditions looks as follows [1]:

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

Author used approximation method called Oustaloup, described by the following formula [13]:

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

where:

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

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

$$ \omega_{z1} = \omega_l \sqrt{\eta} \quad (6) $$

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

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

where: k – gain (adjusted so that both sides of (3) have unit gains at 1 rad/s [13]), q – the fractional order (real number), N – order of the finite transfer function approximation, ω_l – low frequency limit, ω_h – upper frequency limit.

3. Test stand structure

During the design process, it was assumed that test stand should:
- allow the measurement of the actuator position of the drive and its changes over time,
- allow to quick generate code from the MATLAB/Simulink software,
- allow to implemented fractional PD controller on the PLC,
- have the possibility of quick and efficient testing of advanced control systems based on fractional order PD,
- have the possibility of quick reconfiguration of hardware electro-hydraulic drive and its control system, for the future research.

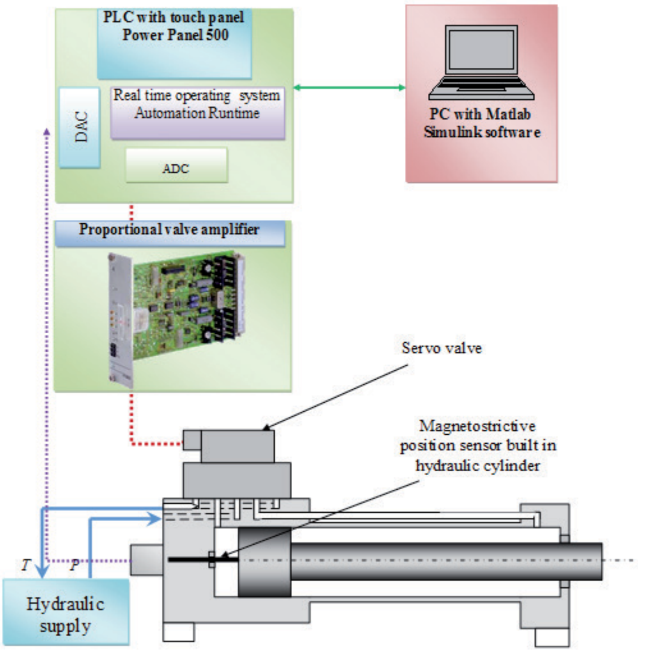

Fig. 1. Laboratory test stand scheme
Rys. 1. Schemat stanowiska laboratoryjnego

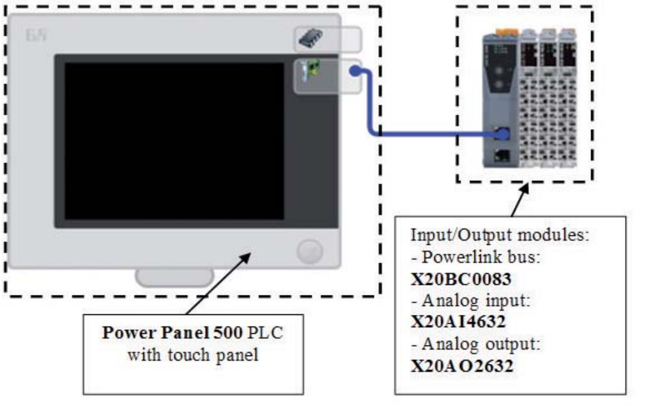

Fig. 2. PLC scheme
Rys. 2. Schemat konfiguracyjny sterownika PLC

Laboratory stand is consist of the mechanical and control part (fig. 1). Control system is based on PLC controller with resistive touch panel type B&R Power Panel 500.

The PLC is based on CPU type Intel Atom 1.6 GHz (fig. 2). System was running under real-time operating system type Automation Runtime [14].

The task responsible for the fractional order controller worked with a time base of 0.4 ms. Visualization was performed in steps of 10 ms, in order to not loading the CPU of PLC. The control program is written in Structured Text and ANSI C. It has been divided into several tasks made of a certain determinism of time. With the same timebase, task responsible for communication between the input/output modules and PLC are worked. Communication was carried out using the Powerlink interface [13].

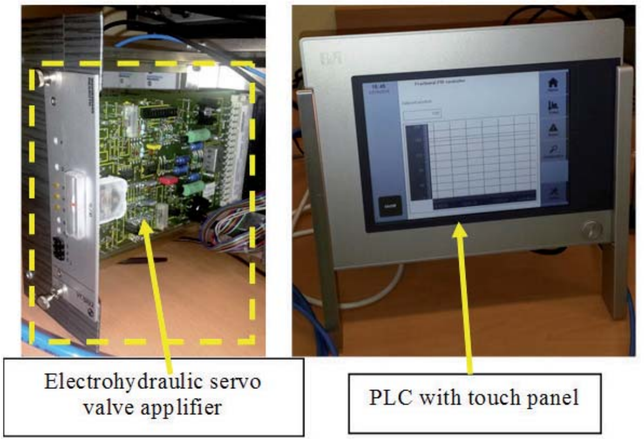

Fig. 3. View of the control electronics
Rys. 3. Elektronika sterująca

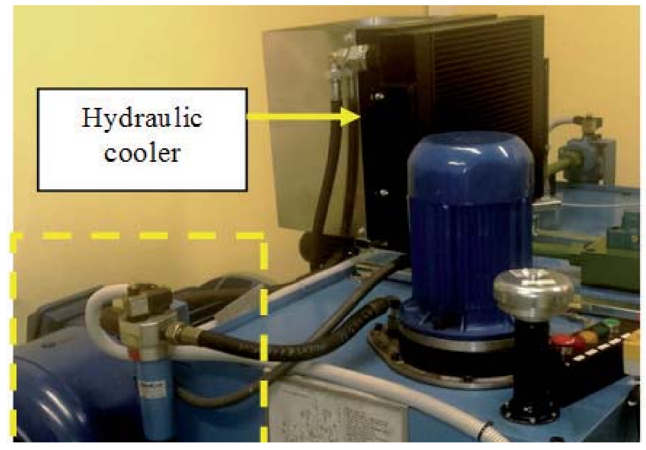

Fig. 5. View of the hydraulic power supply
Rys. 5. Zasilacz hydrauliczny

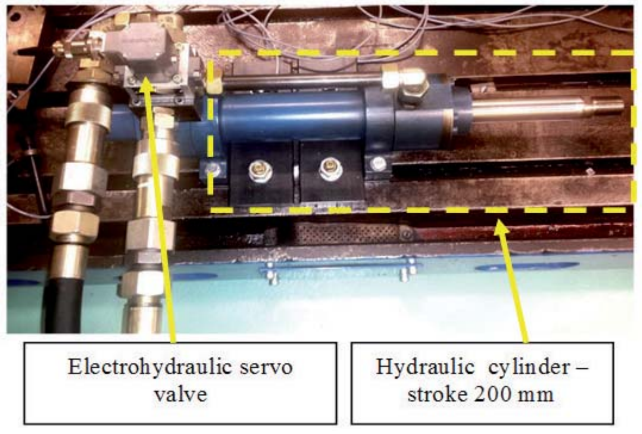

Fig. 4. Hydraulic cylinder with servo valve
Rys. 4. Siłownik hydrauliczny z zaworem

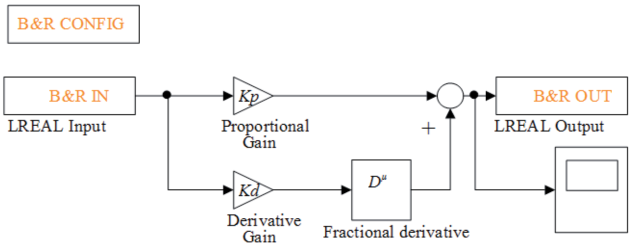

Fig. 6. MATLAB/Simulink model used for code generation
Rys. 6. Model regulatora zastosowany do generowania kodu

The mechanical part (fig. 4) consist of a hydraulic cylinder combined with a Bosch Rexroth servo valves type 4WS2EM10-45. Main valve parameters are: nominal size 10, series 5X, maximum operating pressures 315 bar, maximum flow 180 l/min. The cylinder was equipped with a magnetostrictive position sensor. The stroke of the hydraulic actuator was 200 mm. The diameters of the piston and the piston rod respectively, were $A = 40$ mm and $Aa = 63$ mm.

The testbed is equipped with hydraulic power supplier with the following parameters: the power of 37 kW, maximum flow rate of 100 dm³/min, maximum pressure $p_0 = 40$ MPa, filtration at 6 microns. Authors used non-zinc hydraulic oil with high viscosity index type: Draco HV 46 Premium Oil. The oil temperature during experimental investigation was equal to the constant 45 °C. It was important because of temperature influence on the oil viscosity and therefore electro-hydraulic drive's piston movement. The temperature was controlled by use of dedicated cooler.

Author implements the thread and the libraries which allowing user to generate code directly from MATLAB/Simulink software (fig. 6) [13]. Automation Target for Simulink (B&R) providing additional Simulink blocksets for variables and parameters exchange. The variables declared in the Simulink are connect to the output/input of PLC modules. Significant is the fact, from the practical reason, that the generated C code can be modified directly on the PLC software.

4. Initial experimental investigations

The aim of the initial test was to verify the effect of adjusting the fractional order PD$^{\mu}$ controller coefficient. The electro-hydraulic drive is tested by used of the step response signals, with use of controller described by following formula:

$$G_{FOPD}(s) = k_p + k_d \cdot s^{\mu} \tag{9}$$

where: k_p – gain coefficient, k_d – differential coefficient, μ – fractional coefficient.

The schema of control system structure is presented in fig. 7.

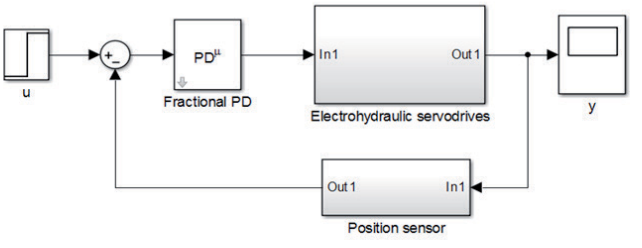

Fig. 7. Scheme of the controller system
Rys. 7. Schemat układu regulacji

The experiment on real object is performed for the supply pressure $p_0 = 6$ MPa. The results are shown in fig. 8, 9, 10. First step was to test of the control system in open loop. The collected data was shown in following fig. 8, 9. The collected data can be used for the future identification of the electro-hydraulic drive parameters, finding zero position of valve spool, proper work of control electronics, and can be used in modelling.

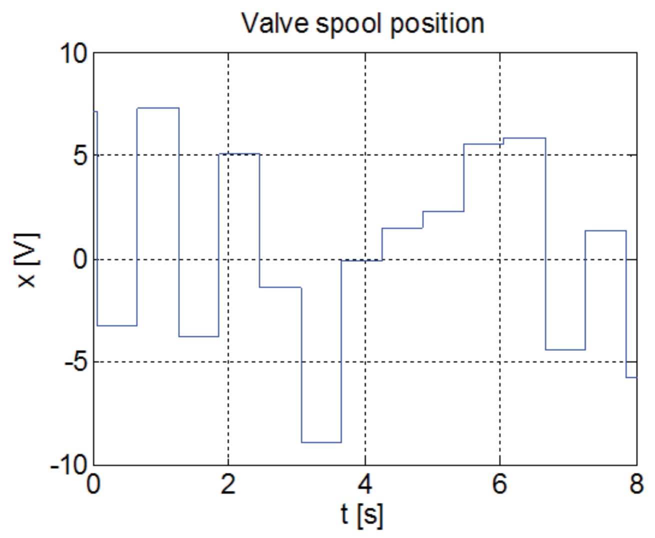

Fig. 8. Valve spool position – open loop test
Rys. 8. Pozycja suwaka zaworu (układ otwarty)

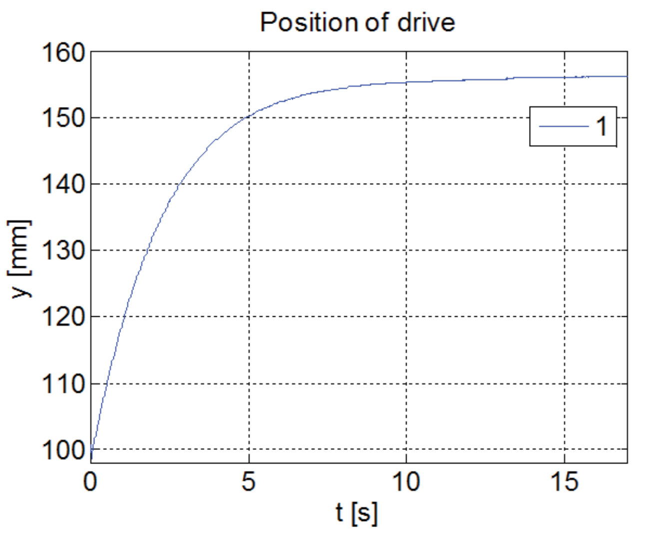

Fig. 10. Step response for $k_p = 150$, $k_d = 0$
Rys. 10. Odpowiedź skokowa napędu dla $k_p = 150$, $k_d = 0$

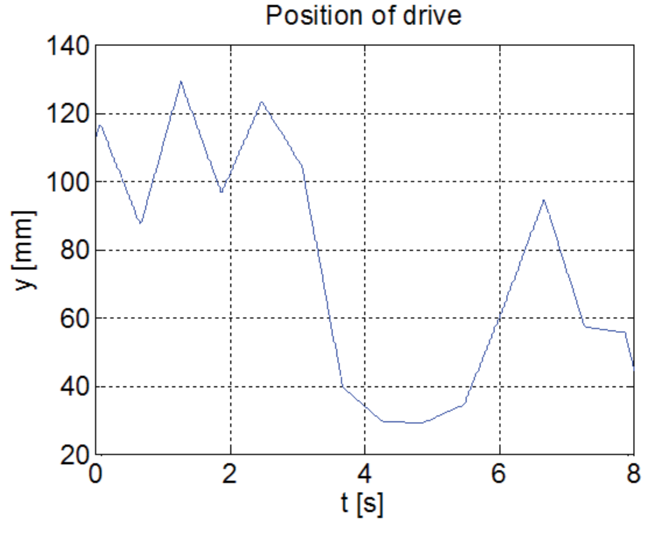

Fig. 9. Drive position correspondent to valve opening (fig. 8) – open loop control
Rys. 9. Pozycja tłoczyska siłownika (układ otwarty)

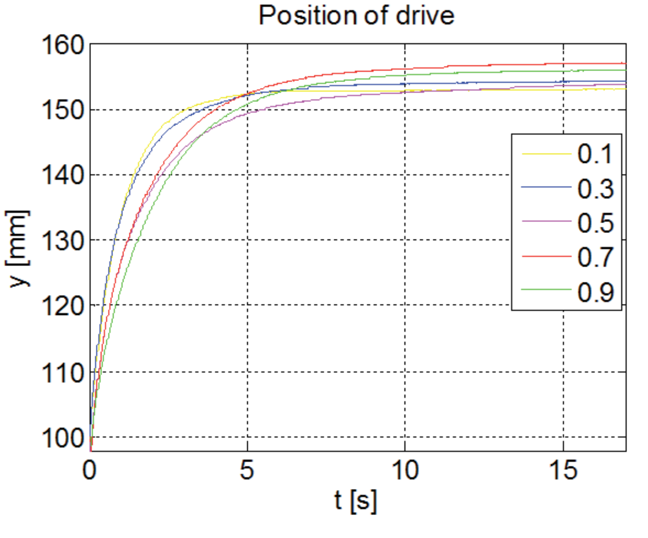

Fig. 11. Step responses for $k_p = 150$, $k_d = 100$ and $\mu = 0.1, 0.3, 0.5, 0.7, 0.9$
Rys. 11. Odpowiedzi skokowe dla $k_p = 150$, $k_d = 100$ i $\mu = 0,1; 0,3; 0,5; 0,7; 0,9$

Next step was to check of work the controller based only on proportional gain. In the fig. 10 a small fixed error (about $e = 1$ mm) has been noticed.

Obtained step responses for fractional order PD^{μ} regulator (piston displacement y) are shown in fig. 9. Order of Oustaloup approximation method N was equal to 5 (influences the accuracy). The order of the equation influences the accuracy of the mapping. The time constant T_{dom}, which is time necessary to reach 0.63 of its final value, is equal to about 4 s. Following equations described used controller:

$$G_{FOPD}(s) = 150 + 10 \cdot s^{0.1} \quad (10)$$

$$G_{FOPD}(s) = 150 + 10 \cdot s^{0.3} \quad (11)$$

$$G_{FOPD}(s) = 150 + 10 \cdot s^{0.5} \quad (12)$$

$$G_{FOPD}(s) = 150 + 10 \cdot s^{0.7} \quad (13)$$

$$G_{FOPD}(s) = 150 + 10 \cdot s^{0.9} \quad (14)$$

The movement is started from the central position of the piston, because of stiffness transition in the length of the cylinder (result of the liquid compressibility).

Figure 12 shows fractional derivative signal influence of controller given on the servo valve amplifier. Changing denominator of fraction derivative has huge impact on controller work.

Next step was to test of the influence only the fractional derivative part of the equation for the positioning of the drive's piston.

Tests were performed for the following parameters (fig. 13):

$$G_{FOD}(s) = 20 \cdot s^{0.1} \quad (15)$$

$$G_{FOD}(s) = 20 \cdot s^{0.5} \quad (16)$$

$$G_{FOD}(s) = 20 \cdot s^{0.9} \quad (17)$$

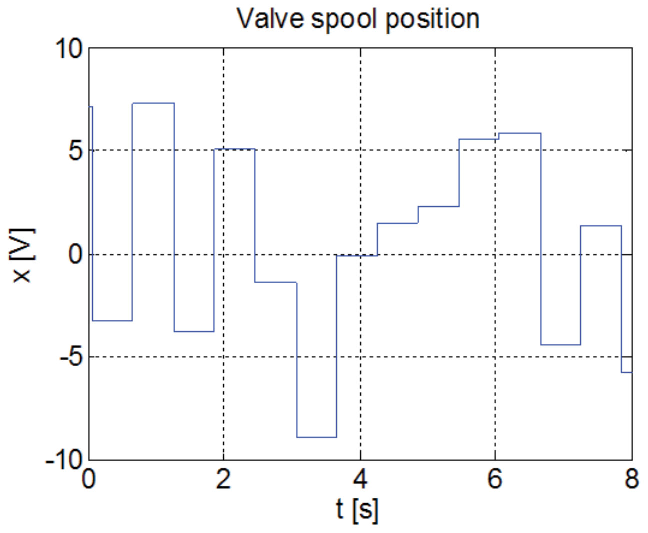

Fig. 12. Fractional derivative influence (k_p = 150, k_d = 100, μ = 0.1, 0.5, 0.9)

Rys. 12. Wpływ członu różniczkującego niecałkowitego rzędu na prace regulatora (k_p = 150, k_d = 100, μ = 0,1; 0,5; 0,9)

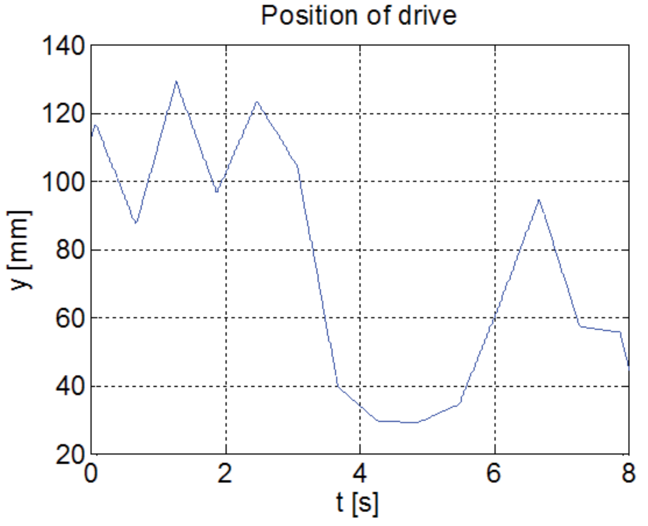

Fig. 13. Step responses for k_p = 0, k_d = 200, (power of s denominator equal to 0.1, 0.5, 0.9)

Rys. 13. Odpowiedzi skokowe dla k_p = 0, k_d = 200, (μ = 0,1; 0,5; 0,9)

5. Conclusion

This paper presents here research focus on initial experimental tests of fractional order controller implementation in electro-hydraulic drives. In this paper the laboratory stand description for testing the factional order controller is presented. The mechanical part consist of a hydraulic cylinder combined with the servo valves. Control system based on PLC with touch panel.

Author test drive with step response in open and close loop. During experiment individual coefficient for fractional PD regulator was change. Because of the small fixed error, there is importuned to extend regulator of the integral coefficient in future research. Also the obtained results will be combine with the data collect from the classical non-fractional order PD controller.

Performed test stand made allowed to conduct further comprehensive investigations of used fractional order PID controller and modeling of electro-hydraulic drives.

Acknowledgements

This paper was supported by the Polish Ministry of Science and Education, grant no. 02/22/DSMK/1332, Poland.

References

1. Chapple P., *Principles of Hydraulic System Design*. Coxmoor Publishing Company, Oxford, 2003.
2. Cundiff S.J., *Fluid Power Circuits and Control Fundamental and Applications*. CRC Press, Boca Raton, London, New York, Washington 2000.
3. Dzieliński A., Sierciuk D., Sarwas G., *Some applications of fractional order calculus*, "Bulletin of the Polish Academy of Sciences Technical Sciences", Vol. 58, No. 4, 2010, 583–592, DOI: 10.2478/v10175-010-0059-6.
4. Zhao J., Wang J., Wang S., *Fractional order control to the electro-hydraulic system in insulator fatigue test device*, "Mechatronics", Vol. 23, No. 7, 2013, 828–839, DOI:10.1016/j.mechatronics.2013.02.002.
5. Mohammad Reza Faieghi and Abbas Nemati (2011). *On Fractional-Order PID Design, Applications of MATLAB in Science and Engineering*, Prof. Tadeusz Michalowski (Ed.), ISBN: 978-953-307-708-6, InTech, DOI: 10.5772/22657,
6. Duarte Valerio, Jose Sa da Costa, *Tuning-Rules for Fractional PID Controllers*, Fractional Differentiation and its Applications, Vol. 2 Part: 1, 28–33, DOI: 10.3182/20060719-3-PT-4902.00004, 2006. Available from: http://www.intechopen.com/books/applications-of-matlab-in-science-and-engineering/onfractional-order-pid-design.
7. Tepljakov A., Petlenkov E., Belikov J., *FOMCON: a MATLAB toolbox for fractional-order system identification and control*, "International Journal of Microelectronics and Computer Science", Vol. 2, No. 2, 2011, 51–62.
8. Duarte Valério, José Sá da Costa, *Ninteger: A Non-Integer Control Toolbox for MATLAB* [On-line], 2005. Available: http://web.ist.utl.pt/duarte.valerio/FDA04T.pdf
9. Tenreiro Machado J.A., Silva M.F., Barbosa R.S., Jesus I.S., Reis C.M., Marcos M.G., Galhano A.F., *Some Applications of Fractional Calculus in Engineering*, "Mathematical Problems in Engineering", Vol. 2010, p. e639801, DOI: 10.1155/2010/639801.
10. Rybarczyk D., Sędziak D., Owczarek P., Owczarkowski A., *Modelling of Electrohydraulic Drive with a Valve Controlled by Synchronous Motor*, Advances in Intelligent Systems and Computing, ISBN 978-3-319-15796-2, 215–222, Springer International Publishing Switzerland 2015, DOI: 10.1007/978-3-319-15796-2_22.
11. Oprzędkiewicz K., Mitkowski W., Gawin E., *An Estimation of Accuracy of Oustaloup Approximation*, in *Challenges in Automation, Robotics and Measurement Techniques*, R. Szewczyk, C. Zieliński, and M. Kaliczyńska, Eds. Springer International Publishing, 2016, 299–307, DOI: 10.1007/978-3-319-29357-8_27.
12. Kaczorek T., *Selected Problems of Fractional Systems Theory*. Springer Science & Business Media, 2011.
13. Merrikh-Bayat F., *Rules for selecting the parameters of Oustaloup recursive approximation for the simulation of linear feedback systems containing $PI^{\lambda}D^{\mu}$ controller*, "Communications in Nonlinear Science and Numerical Simulation", Vol. 17, No. 4, 2012, 1852–1861, DOI: 10.1016/j.cnsns.2011.08.042.
14. B&R Automation, from http://www.br-automation.com/, accessed on 2016-02-13.

Zastosowanie regulatora PD niecałkowitego rzędu w napędzie elektrohydraulicznym

Streszczenie: W artykule opisano wstępne badania dotyczące zastosowania regulatora niecałkowitego rzędu w napędzie elektrohydraulicznym. Jako obiekt badań posłużył siłownik hydrauliczny połączony z serwozaworem. Układ sterowania zbudowano w oparciu o sterownik PLC z panelem dotykowym. Napęd poddano testom z zamkniętą i otwartą pętlą sprzężenia zwrotnego. Przebadano wpływ zmiany wartości poszczególnych parametrów regulatora niecałkowitego rzędu, w tym stopnia części różniczkującej.

Słowa kluczowe: regulator niecałkowitego rzędu, napęd elektrohydrauliczny, serwozawór

Dominik Rybarczyk, PhD Eng.
dominik.rybarczyk@put.poznan.pl

Employed in Division of Mechatronics Devices in Poznan University of Technology. His researches interesting focus on control of electro-hydraulic drives, design of mechatronics devices and programming of PLC controllers. He is the author of about 30 publications.