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AN ANALOG-DIGITAL HYDRAULIC CYLINDER VELOCITY CONTROL SYSTEM FOR MOBILE MACHINES

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Abstract

Hydrostatic drive systems with linear actuators are commonly used in variety of mobile machines and vehicles. One of important aspect of its operation is cylinder velocity control in variable operating conditions, such as different load, pump pressure and engine rotational velocity. The aim of this article is to create an algorithm, which would control velocity of a hydraulic cylinder used in such systems. One way to create cylinder velocity control system is to perform an identification, which would characterize this system. To do this work it was appropriate to use test stand with excavator equipment. The first part of the article includes the description of the stand and enumerates parts that compose it. Correct work of the control system is possible through use of a proper controller. For achieving a desired purpose, a PID controller was used with some modifications improving system's operation. The controller parameters were tuned based on the model of the system, obtained on the basis of estimation, for different operational conditions. To do this, a tool of MATLAB Simulink called Parameter Estimation was used. The control algorithm, in automatic mode, makes system tuning based on coefficients array. The final stage of the research work was to conduct verification tests, which let to assess a correctness of the created and proposed control system.

Keywords: *transport, simulation, control system, mobile machine, hydraulic cylinder, PID controller*

1. Introduction

Nowadays, many disciplines of science are based on an appropriate use of physical phenomena. One of such disciplines is hydraulics, a developing rapidly domain that is very useful and effective. Currently, hydraulic systems are being used more commonly due to their usefulness in everyday operation of each plant. Growing interest in using hydraulic systems is caused by the fact that they have multiple advantages [4, 5].

One of many advantages of these systems is the possibility to receive great forces from a small device, impossible to obtain in any other way. Another very important aspect of hydraulic systems is the possibility to apply step less control. Because of the many advantages, these systems are widely used in building and constructing machines. It is important to be aware of the fact that in each hydraulic system, particular elements, such as pumps, valves, actuators and filters, play a significant role. In a great number of such devices, hydraulic cylinders as linear actuators are used to drive mechanical elements. A proper use of these devices requires applying the corresponding control system to regulate their parameters [1, 3].

This article presents a control system of the hydraulic cylinder, together with selection of controller parameters. To make it, MATLAB Simulink tools, which allow determining the characteristics of the system, were used. An advantage of using these tools is the possibility to conduct further attempts of tuning a proper parameter of PID controller without making any changes into test stand. Tuning a proper adjustment on the test stand without using MATLAB Simulink tools could adversely influence devices constructing the test stand.

Taking all these assumptions into account, it can be stated that technical software is also helpful in stepless regulation of devices, including cylinder velocity, through adjusting a proper value by different simulation platforms.

2. Test stand structure

To create and test such described control system, the test stand with an excavator's stick was used. To execute properly working control system it was necessary to know how the excavator is built, including kinematic and hydraulic systems.

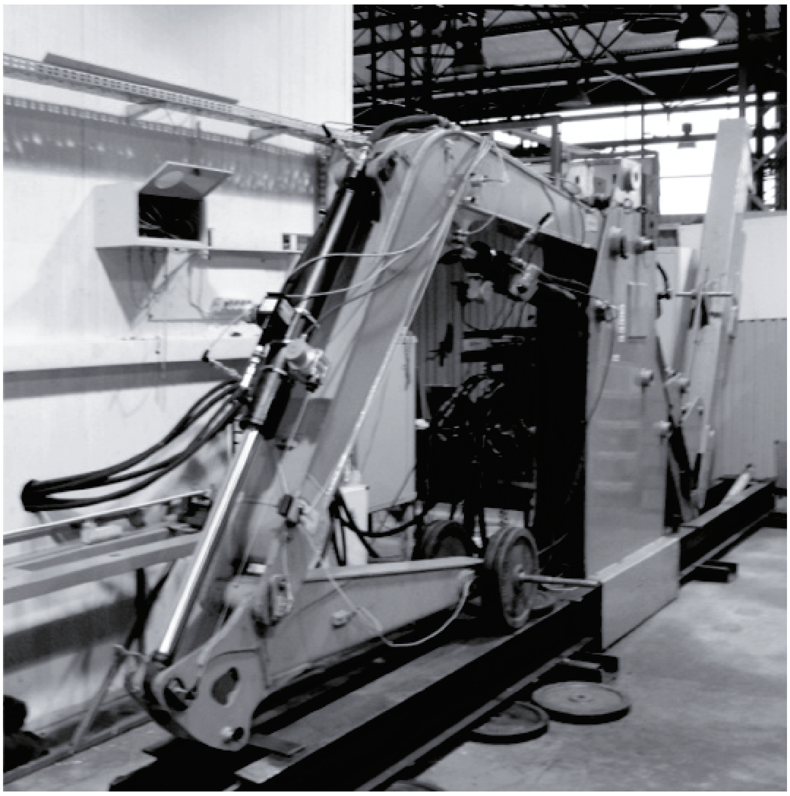

Fig. 1. View of the test stand

Hydraulic system is responsible for steering a motion of operating elements. This system enforces a liquid's flow in the appropriate way, which causes a motion of an excavator stick with the use of cylinder movement. A view of the test stand with the hydraulic equipment is presented in the Fig. 1, while diagram of hydraulic circuit, with all components, which supply an excavator stick, are illustrated on the right side of the Fig. 2.

A test stand that is properly made, considering its kinematic features and also all hydraulic elements, is useless if it is not equipped with appropriate measuring elements and control system. Test stand should be equipped with sensors measuring the parameters that are used then to control it. It is also necessary to include devices, which send signals to controlled actuators, by the use of electro hydraulic valves. To perform the measuring task, it was useful to apply transducers with encoders, which allow to measure displacement and velocity. Additionally, to examine the correctness of the hydraulic system, pressure transducers were used.

Components of the hydraulic system are 1 – electric motor; 2 – pump PV046_UPG produced by Parker; 3 – direct operated proportional distribution valve D3FP produced by Parker; 4 – boom cylinder: ø100/60x1060/664.5; 5 – stick cylinder: ø90/55x1020/675.5. In addition to this, the hydraulic system is equipped with relief valves, pipes, filters, reservoirs, etc.

Because the operation of the hydraulic systems needs to be constantly supervised, the system was equipped with a great variety of sensors, enabling recording the changes in physical values. Recording and processing these changes allow applying this information in feedback from the system. It was also able to register these signals in time and to graph them. It could be helpful for further analysis and improvement of a test stand.

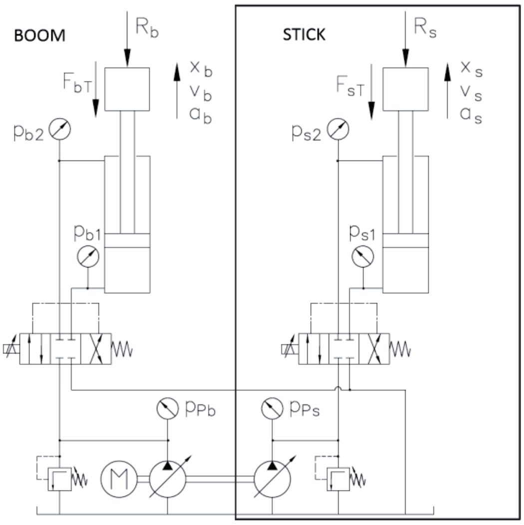

Fig. 2. Scheme of the hydraulic system

3. Identification research

The aim of the identification research was to get data from the test stand and consequently, use them to create a model, which could simulate operation of a real stand system. Identification tests of the system were conducted through supplying voltage to a proportional valve in step function way. The identification research mentioned above was conducted for four different values of pump pressure, two different pump rotational speed values and with certain load and without it. For each of the combinations of three variables conditioning the work of the system, the changes in cylinder velocity were registered.

An industrial computer xPC TARGET programmes a controller of a proportional distribution valve, wherein communication between them is realised by voltage signal (± 10 [V]). The last element of the control system, which allows creating a steering program, is a personal computer HOST with MATLAB Simulink software. A communication between personal and industrial computers is established by TCP/IP (or RS232) link. A scheme presenting the control system of a proportional distribution valve is depicted in Fig. 3.

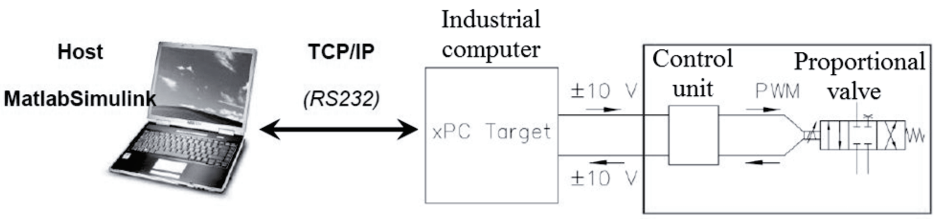

Fig. 3. Diagram of proportional distribution valve control subsystem

There are a few approaches of identification and mapping of the system [2]. One of them is the method, which is based on dynamic model described by differential equations. This method allows predicting the behaviour of the system without building it, but with some simplification, because it is difficult to create, especially such effects as friction or nonlinear flow characteristics. Applying the method mentioned above could be very time-consuming. Another way of system identification is applying data from the test stand. This method preserves credibility because of using authentic values. A necessity to conduct a great number of measurements is a great limitation of this method to use it as is. Applying this method is possible through use of a module called System Identification Toolbox from MATLAB Simulink application. This module, being based on real measurement data and using different mathematical approximations, allows to identify the system.

An initiation of work with this module was started by importing measurement data, defining input and output signals and also time of their sampling. Imported data could be transformed by a user through e.g. deleting mean value, filtering the data and choosing an appropriate range, which is the most important during further processing. The module has user-friendly graphic interface, so thanks to that, it is easy to see actual results of identification process.

Employing the System Identification Toolbox and Hammerstein – Wiener model, a few estimations with different parameters characterising the mentioned model have been made. Fig. 6 depicts a few of the most suitable identifications of the real system. Each identification was get by changing parameters, which characterise Hammerstein – Wiener model.

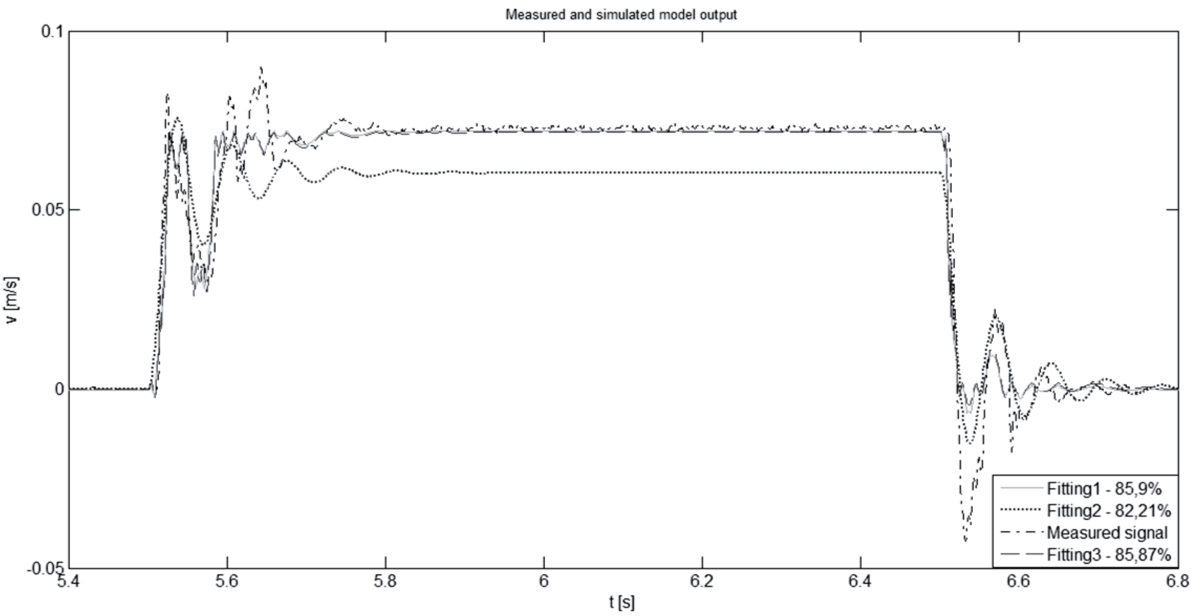

Fig. 4. Stick cylinder velocity approximation with Hammerstein – Wiener model

Analysing the results of the identification, it has been noticed that the chosen model satisfactorily define the examined system, therefore it is possible to proceed with works using this model. The closest approximation of the analysed system was obtained for Hammerstein – Wiener model and amount to 86%. Only the big and slowly fading oscillation of the cylinder's velocity do not sufficiently coincide with chosen identification model.

The best identification, Fitting 1 in Fig. 4, coincides with measured velocity signal for steady state values. Step change of cylinder velocity causes its oscillations, which are taken into consideration by identification model only in certain cases. Approximation of each swing is almost impossible by the selected model and any attempt of its improvement leads to complicated calculations of the program. A result of the identification could be imported to the variable and it could be used in MATLAB Simulink with other blocks, which could create a control system. Thanks to that, it is possible to substitute the composed system with one block. Other identifications from the data acquired from the test stand were conducted in the similar way as presented above. Overall, sixteen identifications were conducted. These amounts determine all combinations of parameters, for which data were retrieved from the test stand.

4. Control system with PID controller

The xPC Target computer has built-in components responsible for retrieving measurement data from a test stand and sending signals to control devices. Block diagram of a system, which allows communicating with external devices, built on MATLAB Simulink platform, is presented in the

Fig. 5. This model is composed of blocks enabling recording data, sending signals to control units, plotting / graphing data on the monitor and defining the structure of the control system.

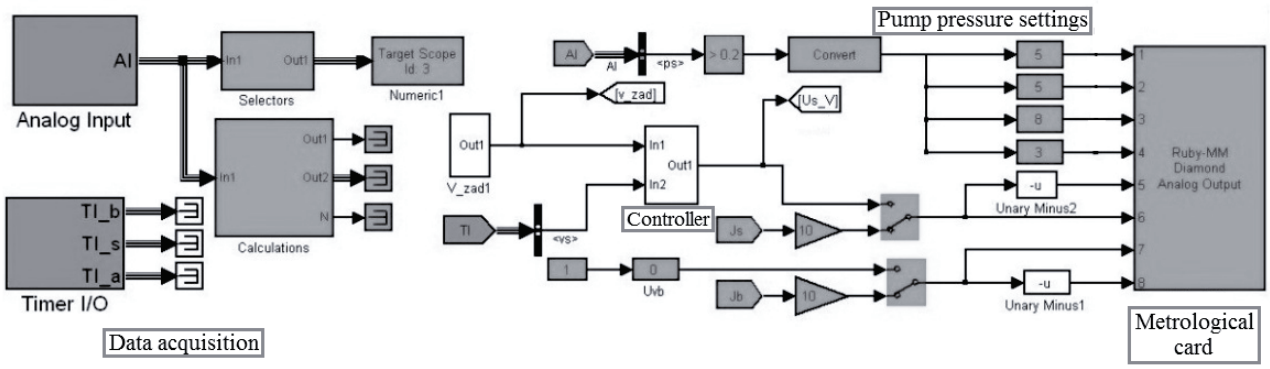

Fig. 5. The structure of the model created in MATLAB Simulink

In the presented algorithm, it is possible to switch between manual control (using joysticks) and automatic control. Automatic control requires using a control algorithm with proper adjustments. This action enables getting the demanded cylinder velocity in a smooth way, without overloading the system. In this model, PID controller with a required improvement was applied. A scheme of a control algorithm is presented in Fig. 6.

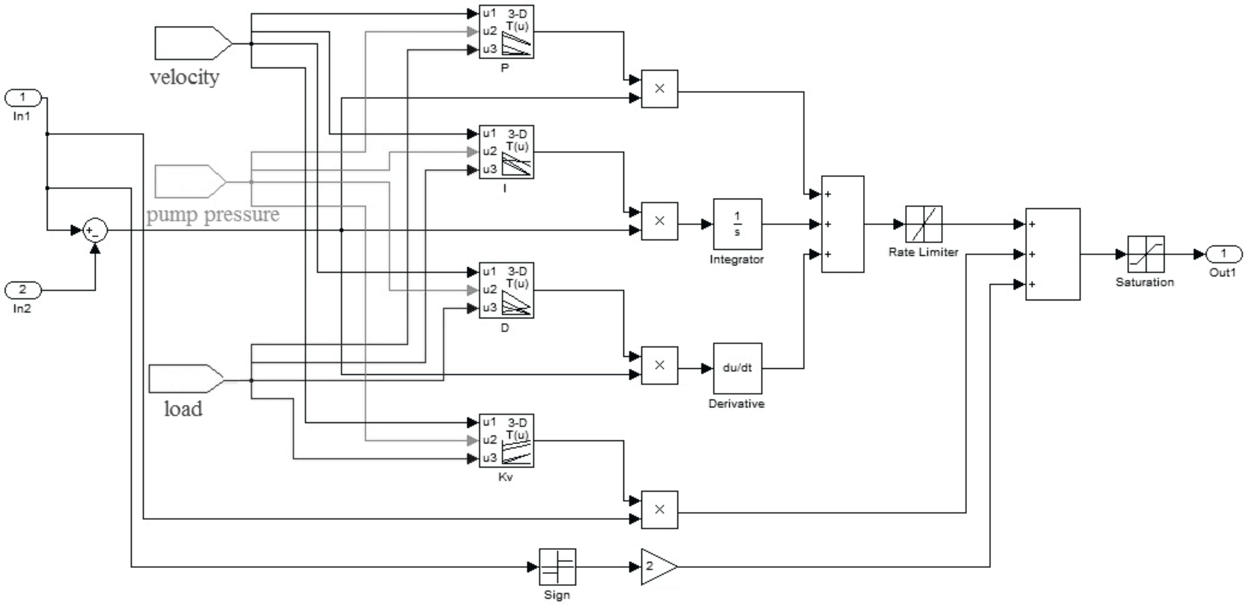

Fig. 6. The scheme of control algorithm with Lookup-Table blocks

A correct control of the system is possible by using not only basic links of PID controller, but also a few other blocks. One of them is a “Rate Limiter” block, which task is to limit the speed of output signal’s rise or fall. Because rapid changes of output signal could cause water hummer phenomena in hydraulic circuit, therefore “Rate Limiter” was implemented. Another very important element, which was used in this control algorithm, is a “Saturation” block. Its task is to limit output signal from -10 to 10 [V]. Setting this value is essential because the electronic control unit of the proportional valve works on the mentioned range of voltage.

While considering the controller’s action, it is important to pay attention to the dead zone of proportional valve. It causes that the control unit of proportional distribution valves does not work with voltage from -2 to 2 [V]. To avoid such situation it is necessary to use “Sign” block with double gain. This procedure allows sending an appropriate value of output signal to control unit of proportional distribution valves. An additional modification used in the created controller is a gaining unit called "Kv." Using this block allows approaching to demanded value faster, through enhancing an input signal. "Kv" parameter was selected from coefficients of P, I and D of control algorithm, during optimisation of a proper adjustment.

Correct work of a controller is possible, when its parameters are tuned properly. Tuning proper adjustments of control algorithm was realised using "Parameter Estimation" option from toolbar called Tools. After indicating an input signal, which is the demanded velocity, and an output signal (cylinder velocity), parameters are being adjusted using "Parameter Estimation" tool. The parameters P, I, D and Kv are selected in such a way as to get the demanded velocity in the best way. These parameters were tuned for all combinations, for which data were retrieved from the test stand.

Tuning proper adjustments of the control algorithm for all system identifications were realised in the same way as shown in the Fig. 7. After conducting all the tuning, it was possible to create a matrix of the demanded parameters for all combinations of input values. A 3-D matrix with adjustments of PID controller for three different input signals (pump pressure setting, pump rotational velocity and load secured at the end of stick) was created. This task was realized using Lookup-Table from MATLAB Simulink library

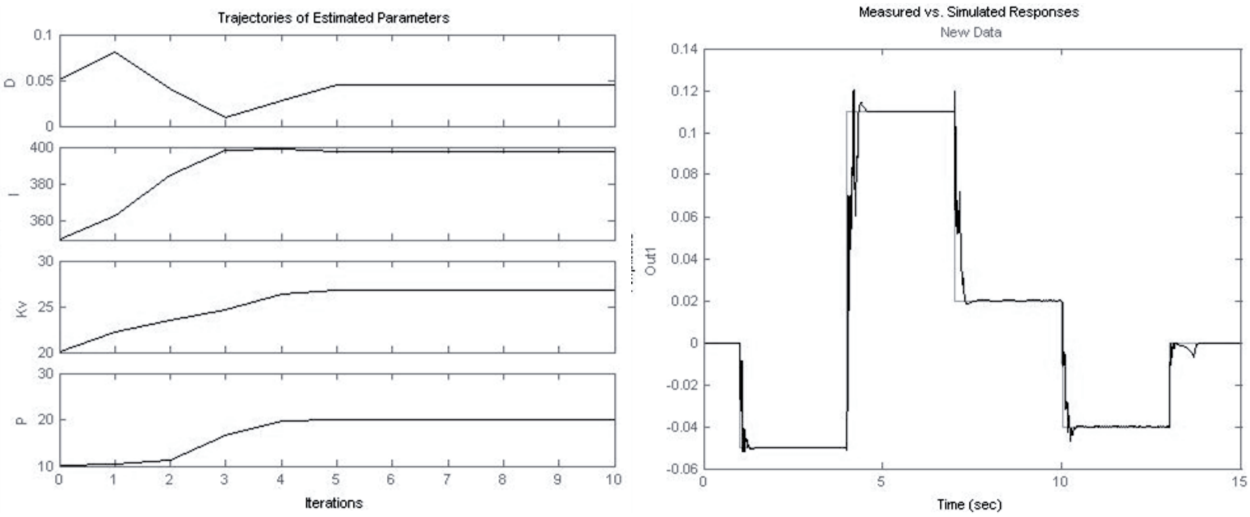

Fig. 7. Changes of the controller coefficients during optimisation process and received velocity graph

5. Verification research

The final stages of the research were experimental tests, during which measurements were implemented to allow examining a correctness of the created control system. The activities executed on the test stand let to state how useful is the method applied for velocity control of a hydraulic cylinder. During examination research, a series of tests were executed and data of the values important for the proper work of the system were registered.

Graphs presented in the Fig. 8 were getting for the following settings: pump rotational speed – 1000 rpm, pump pressure setting – 7.5 MPa and external load – 80 kg. The plot shows a comparison between demanded and real velocity of excavators implement stick cylinder. Demanded signal is marked with continuous line and measured with dotted line. A control system, which automatically chooses proper parameters, selects following adjustments for current values of input signals: P = 18.4268, I = 503.0102, D = 0.1146, Kv = 28.0229. These adjustments allowed for getting a demanded velocity by excavators cylinder.

During verification tests, for the data received, it was necessary to conduct a test of quality control. As indicators of quality, settling time and overshoot value were chosen. Each velocity control test consists of five different steps; therefore, five values of overshoot and settling time were determined. In the case of settling time, error band equals 5 %. Fig. 9 presents a way of quality control indicators determining on one of the registered signals (for pump speed n = 1000 $\left[\frac{rev}{min}\right]$, pump pressure adjustment 7.5 MPa and load = 80 [kg]). The Tab. 1 characterises quality of the control system, using described two parameters.

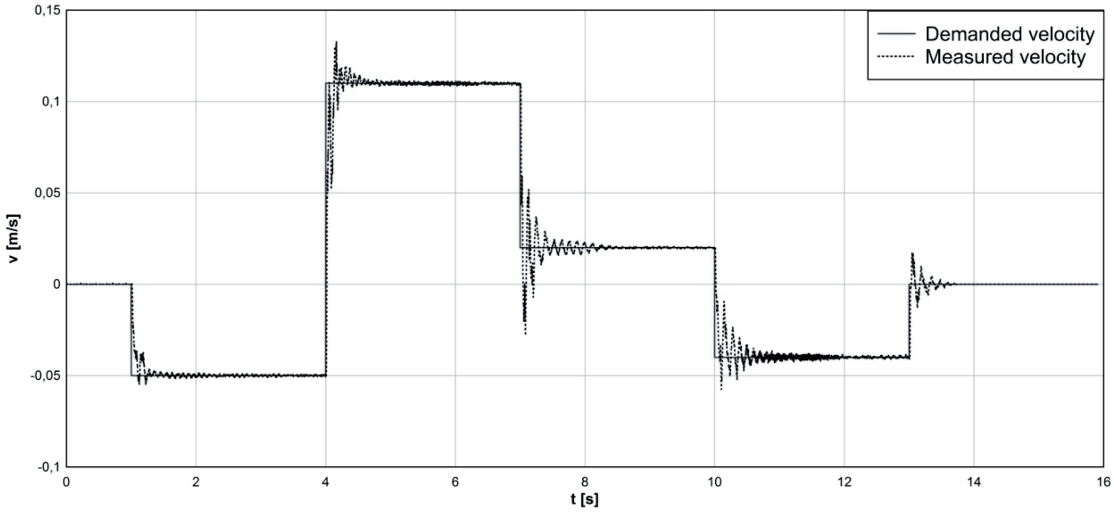

Fig. 8. The comparison between demanded and measured cylinder velocity for the system with bucket load

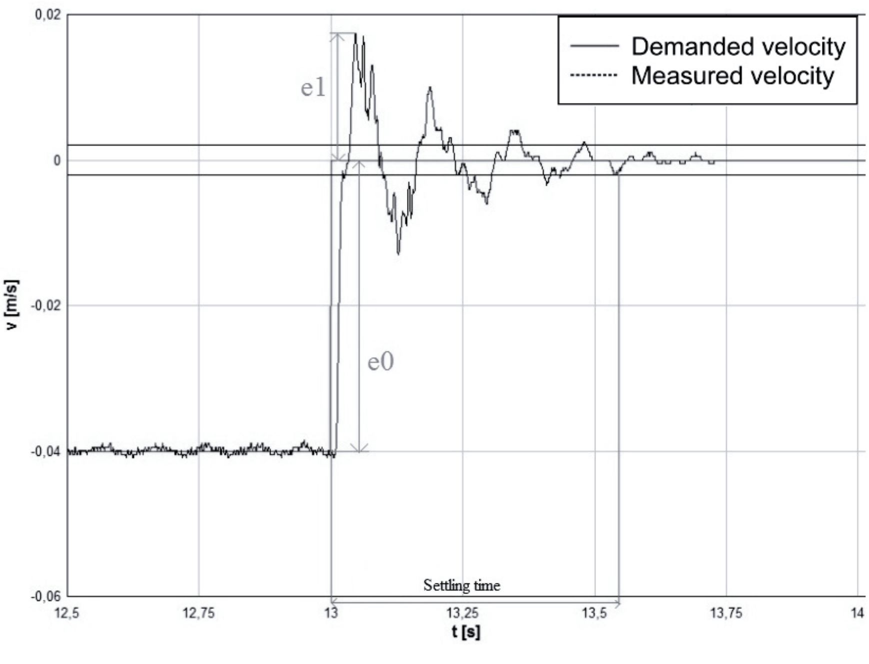

Fig. 9. Illustration of the way of determining overshoots error and settling time

Tab. 1. Overshoot and settling time

Cylinder velocity [mm/s]	Overshoot [%]	Settling time [s]
-50	10.00	0.28
110	12.50	0.24
20	50.00	0.35
-40	29.17	0.51
0	38.75	0.32

6. Summary

This article presents particular stages of creating a control system of cylinder velocity. First part includes a description of an identification method of the analysed system. Identifications are being made with the use of data retrieved from laboratory tests and by putting them into a tool of MATLAB Simulink, called System Identification Toolbox. Identification research was conducted for different system parameters, that is: a pump pressure, a rotational speed of a pump and an extra mass placed at the end of the excavator's stick.

Because the correct work of the system is possible, only by the use of an appropriate controller – to achieve this aim, a PID controller with additional blocks was applied. It was also necessary, to tune controller coefficients. To do this, a tool of MATLAB Simulink called Parameter Estimation was used. Then, a 3D matrix including all the parameters of the controller was created. It was made by the use of 3D Lookup-Table block from Lookup Tables library of Simulink. To this block, signals with previously mentioned system variables (e.g. a pump pressure) were linked. Any change of these parameters results in choosing a particular value from the matrix and putting them into the output of the block.

After performing all these activities, a research work was made to check whether this control system works correctly. Graphs, included in this paper, allow comparing expected and real stick cylinder velocity. Generally, implemented control system has worked properly, only in a few areas of speed changes, some inaccuracies may be observed. It could be explained by poor and insufficient fitting of the identification model, what is especially visible during rapid changes of the actuator speed.

Taking into account above conclusions and notes it can be assumed that the method of identification and the control system applied in this work could be extended and used as a good quality control system of actuator's speed in hydraulic systems. In addition, the main condition of its usefulness is a necessity of accurate identification analysis of each of the system's elements enabling matching a proper adjustment of PID controller.

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