Verification of Control Algorithms with DDE Communication on Real Hydraulic System

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***Abstract*—The paper deals with a real hydraulic system modeling and control by designed digital PID control algorithms in Matlab with using DDE communication. A mathematic-physical description of real hydraulic system is established in a form of nonlinear differential equations on the basis of analytic identification with known physical principles. Also simulation model, created in Simulink, based on nonlinear differential equations for designed PID control algorithms verification purpose is introduced in the paper. The design of digital PID control algorithms is briefly mentioned in the next section of the paper. A flow chart diagram of implementation of main control program with DDE communication between the real system and a computer, on which control algorithms are running, is a part of the paper, too. In the end of the paper results of real hydraulic system control by designed digital PID control algorithms with DDE communication are presented.**

***Keywords*—communication protocol DDE, PLC, digital PID control, real hydraulic system, simulation language Matlab.**

I. INTRODUCTION

The paper deals with modeling of real hydraulic system, which serves as an educational model for identification and control algorithms verification at the Department of Cybernetics and Artificial Intelligence. The paper is also engaged in control of real hydraulic system with designed digital PID control algorithms in Matlab with using DDE communication.

The first part of the paper is devoted to real hydraulic system mathematic-physical description, which was derived in form of nonlinear differential equations on the basis of analytic identification with using known physical principles. Moreover, a hardware structure of real hydraulic system and a way of its connection to the computer is presented. Also simulation model created in Simulink by implementation of nonlinear differential equations for purpose of closed loop control structure with designed PID control algorithms analysis is introduced in the paper, too.

In the next section of the paper a design of digital PID control algorithms is presented. Also a program implementation of DDE communication protocol in the framework of control algorithm running in Matlab is mentioned.

The paper contains results of real hydraulic system control by designed digital PID control algorithms with DDE communication verification in form of control action and controlled output time responses.

II. REAL HYDRAULIC SYSTEM

The real hydraulic system is one of laboratory systems, which serve as educational models for identification and control algorithms verification at the Department of Cybernetics and Artificial Intelligence. It is composed of two cylindrical tanks, which are connected by a tube. Tanks are placed one above another and they constitute a system of tanks without mutual interactions. A liquid is fetched into the first tank from a bathtub through an inlet tube by a pump [1]. It flows out from the second tank back to the bathtub under the thumb of hydrostatic pressure. It is possible to change an intersection size of outlets in both tanks by throttling screws. There are four different intersection sizes.

A schematic illustration of real hydraulic system is depicted in Fig. 1, whereby particular physical parameters are:

S - intersection of tanks,
S_{v1}, S_{v2} - intersection of outlets of both tanks,
h_{max} - height of tanks (maximal liquid level),
$f_m(t)$ - pump's motor frequency,
$h_1(t)$, $h_2(t)$ - current levels of liquid in both tanks.

Sensors, which scan the current liquid level in both tanks are marked as S_{n1} and S_{n2}.

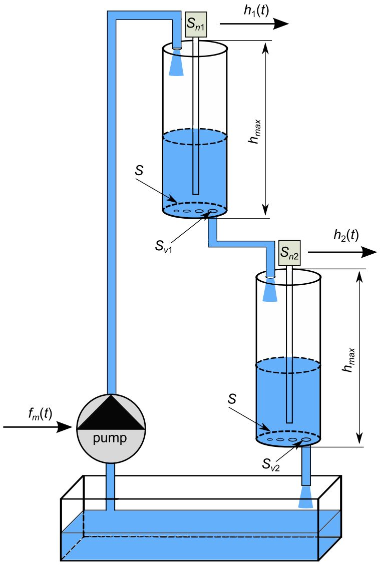

Fig. 1 Hydraulic system – physical principle

The frequency $f_m(t)$ constitutes the only input of laboratory model in term of systemic approach. The frequency $f_m(t)$ is generated by frequency drive [2] according to voltage $U(t)$, which is connected to frequency drive's input from analog card of PLC [3] in the range 0 – 10V. Thus, it is possible to consider the direct value of voltage $U(t)$ as laboratory model's input. There is a linear dependence between the voltage $U(t)$ and frequency $f_m(t)$.

Outputs of laboratory model are represented by current levels of liquid in both tanks $h_1(t)$ and $h_2(t)$, which are measured by sensors [4]. However, the aim of control is to ensure required value of liquid level in the second tank h_{2ref}. Therefore we restrict ourselves to a SISO system control, where the value $h_1(t)$ serves only for demands of PLC program, which handles limit values of particular quantities and emergency conditions.

The change of intersection size of the second tank outlets ΔS_{v2} constitutes a disturbance.

The systemic view of real hydraulic system is depicted in Fig. 2.

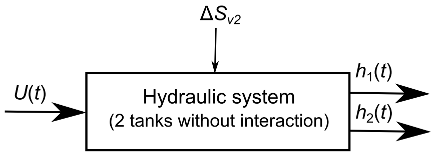

Fig. 2 Hydraulic system – systemic view

A. Structure of real hydraulic system

A complete structure of real hydraulic system is depicted in Fig 3. The real hydraulic system is directly joined to input/output analog card of PLC. The program in PLC, which was created in RSLogix environment [5], provides reading and writing values of particular quantities to the PLC card. Moreover, it safeguards system protection from emergency conditions.

Concurrently, PLC is connected to a personal computer by serial or Ethernet interface. The communication between PLC and PC is carried out in such a way. It is necessary to install software providing DDE server functions to PC. In this case it is RSLinx [6], because PLC is product of Rockwell Automation company [3].

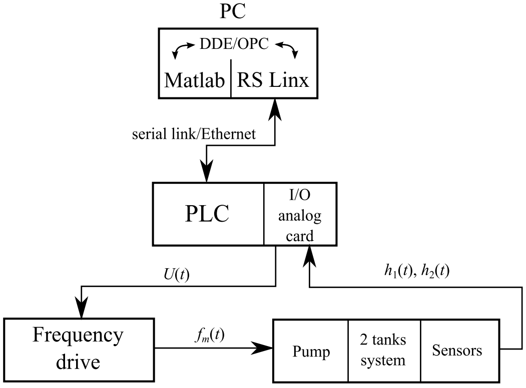

Fig. 3 Structure of real hydraulic system with connection to PC

Mentioned structure of real hydraulic system makes possible to carry out control in two different ways. The simplest way is to implement designed digital PID control algorithms directly to the PLC, which allows to leave out PC of structure in Fig. 3. Creating communication between PLC and PC becomes unimportant in this case. The second approach is based on the control algorithms running in Matlab in PC. This approach is more difficult in term of creating communication. On the other side, it allows to use many advantages of Matlab. I have decided for the second way because I would like to verify predictive control algorithms on the real hydraulic system, which are based on quadratic programming with using *quadprog* function from Optimization toolbox of Matlab in future.

B. Mathematic-physical description of hydraulic system

It is possible to derive nonlinear differential equations by analytic identification with using known physical principles, such as continuity relation or Torricelli's formula:

$$\begin{aligned} \frac{dh_1(t)}{dt} &= \frac{1}{S}\left(k_p U(t) - S_{v1}\sqrt{2gh_1(t)}\right) \\ \frac{dh_2(t)}{dt} &= \frac{1}{S}\left(S_{v1}\sqrt{2gh_1(t)} - S_{v2}\sqrt{2gh_2(t)}\right) \end{aligned}, \qquad (1)$$

which describe hydraulic system dynamics, whereby g is acceleration of gravity. Pump's value k_p was computed from experimental measurements.

It is important to note that it is necessary to establish a linear model, which would represent the dynamics of hydraulic system at properly chosen operating point for digital PID control algorithms design.

C. Nonlinear simulation model of hydraulic system

A nonlinear simulation model of hydraulic system, which is depicted in Fig. 4, was created in Simulink on the basis of nonlinear differential equations (1). The simulation model was used in the analysis of control closed loop with designed digital PID control algorithm dynamics.

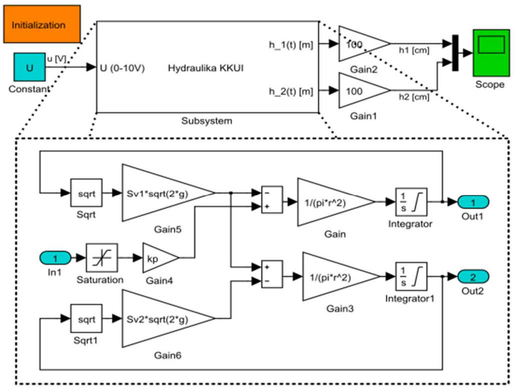

Fig. 4 Nonlinear simulation model of hydraulic system

III. DIGITAL PID CONTROL ALGORITHMS DESIGN

Digital PID control algorithms design starts from the linear model of hydraulic system, which was obtained by nonlinear differential equations (1) linearization in operating point: $U_0 = 4V$, $h_{10} = 0.16m$, $h_{20} = 0.158m$, whereby $h_{\max} = 0.3m$.

The linear model has a form of transfer function

$$F_s = \frac{H_2(s)}{U(s)} = \frac{K}{\left(a_2 s^2 + a_1 s + 1\right)}, \qquad (2)$$

where K is a static gain and a_i are denominator's elements.

It is possible to compute coefficients of continuous PID

$$F_R = P + \frac{I}{s} + Ds, \qquad (3)$$

where P, I and D is proportional, derivative and integration gain.

The optimal module method and the standard form method by Butterworth were used for P, I and D coefficients design purpose. The latter method have been already used in digital PID control algorithms verification on the real system Ball and Plate in [7].

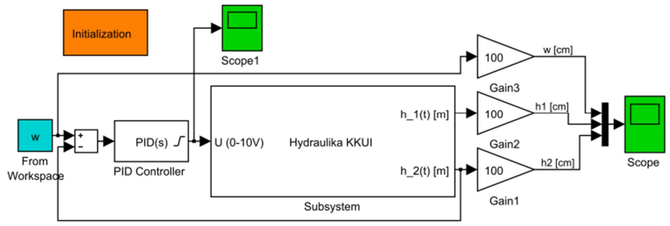

Fig. 5 Closed loop structure for nonlinear simulation model of hydraulic system control

It was found by the analysis of dynamics of the closed loop structure with designed PID control algorithm and simulation model (Fig. 5) that the derivative part in the control algorithm causes very fast increase of liquid level in the first tank. Thus, the maximal liquid level overflow would come into being and PLC program would automatically stop the frequency drive in real system control. For that reason, the digital PI control algorithm, which derivative part is zero, was designed and applied in the real system control structure.

In the case of the optimal module method a matrix form was used for computing *P* and *I* coefficients:

$$\begin{bmatrix} a_1 & -1 \\ a_3 & -a_2 \end{bmatrix}\begin{bmatrix} I \\ P \end{bmatrix} = \frac{1}{2K}\begin{bmatrix} 1 \\ -a_1^2 + 2a_2 \end{bmatrix}, \qquad (4)$$

where coefficients a_i are elements of transfer function's denominator. In the second case the standard form of 3rd order characteristic polynomial of closed loop according to Butterworth was used.

Coefficients of digital PID control algorithm q_i were computed from known values of continuous PID coefficients on the basis of equations mentioned in [8]. A formula for computing the control action, which is implemented in control closed loop for the real hydraulic system control, has form

$$u(k) = u(k-1) + q_0 e(k) + q_1 e(k-1) + q_2 e(k-2)\,, \qquad (5)$$

where $e(k)$ constitutes a deviation between reference trajectory $w(k)$ and current system output value $y(k) = h_2(t)$.

IV. PID CONTROL ALGORITHMS VERIFICATION ON REAL HYDRAULIC SYSTEM

In this case, where aim of the control was fulfilled in simulation model control, designed PID control algorithm was implemented to the main program for real hydraulic system control in Matlab. Matlab functions of DDE protocol and RSLinx tools were used for communication with PLC. It is possible to read data from real system and subsequently change the control action value, which is computed by control algorithm in PC in such a way.

The basic principle of main program with DDE communication and digital PID control algorithm is visible in a flow chart diagram, which is depicted in Fig. 6. There are also Matlab commands providing DDE communication with PLC mentioned in the flow chart diagram.

Results of the real hydraulic system control using digital PI control algorithm, which coefficients were designed by the optimal module method are depicted in Fig. 7. The reference trajectory is a constant function with desired value, whereby another second tank's outlet was opened for a short while in time t = 580s. So, a disturbance was incorporated to control process in such a way.

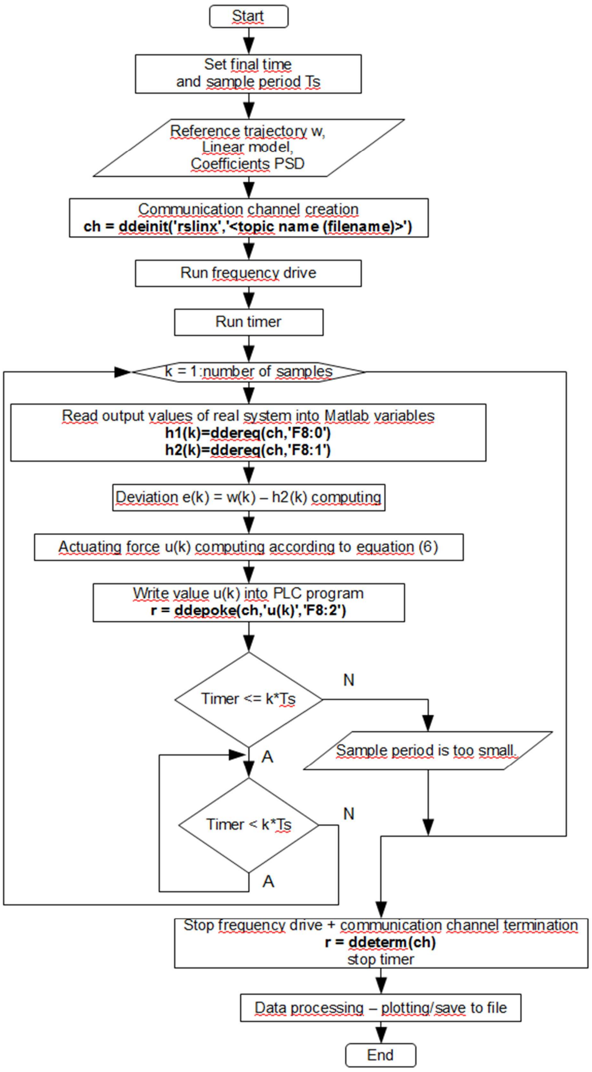

Fig. 6 Flow chart diagram of program with control algorithm using DDE communication

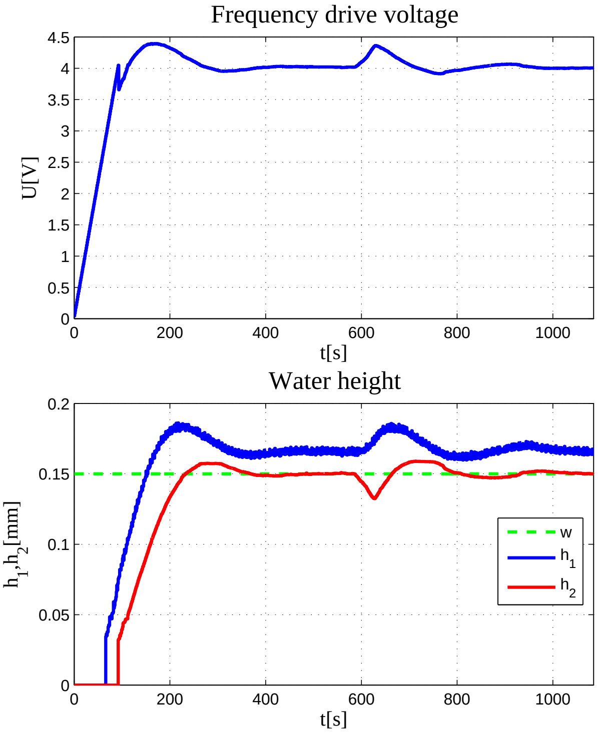

Fig. 7 Results of the real hydraulic system control with digital PI control algorithm designed by the optimal module method

In Fig. 8 results of the real hydraulic system control with digital PI control algorithm designed by the standard form method according to Butterworth are visible. In this case the reference trajectory was variable and control process was not affected by any disturbances.

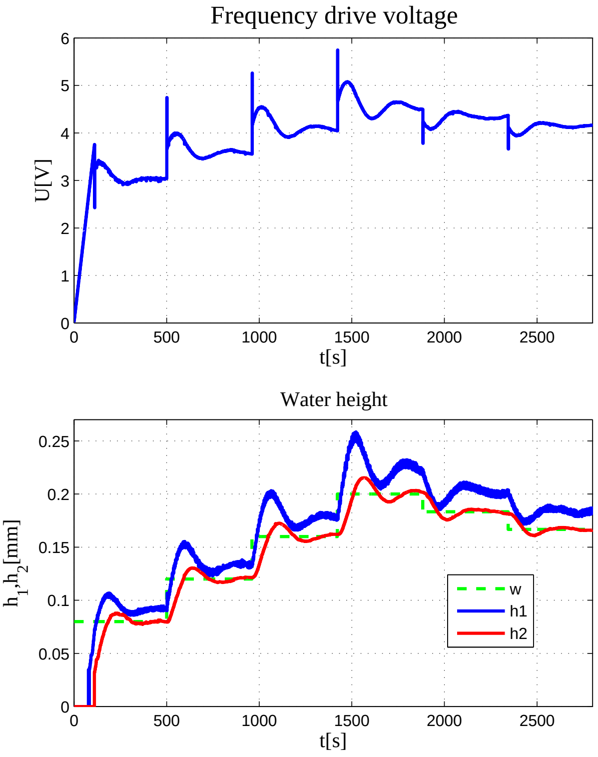

Fig. 8 Results of the real hydraulic system control with digital PI control algorithm designed by the standard form method according to Butterworth

By Fig. 7 and Fig. 8 comparison it is clear that using digital PI control algorithm designed on the basis of the optimal module method causes a smaller overshoot of controlled quantity with the step change of reference trajectory. This fact was confirmed by comparison of real hydraulic system control results, where digital PI control algorithms designed by both methods were used and the reference trajectory was the constant function.

Essentially it can be pointed out that real hydraulic system control with digital PID control algorithms enables to fulfill aims of control. However, it is necessary to note that the maximal liquid level overflow in the first tank does not occur only when the derivative part is close to zero. The digital PI control algorithm, designed on the basis of the linear model for properly chosen operating point, is robust enough to change the desired value of liquid level in the second tank. However, in selection the range of reference trajectory it is necessary to take fact that the liquid level in the first tank is higher than in the second tank into consideration.

V. CONCLUSION

The real hydraulic system, which constitutes an educational model for identification and control algorithms verification at the Department of Cybernetics and Artificial Intelligence was introduced in the paper. Its mathematical description in form of nonlinear differential equations, which served as the base for creating the nonlinear simulation model in Simulink was mentioned.

The main goal of this paper was to present the structure of the real hydraulic system connection to the PC through the PLC and possibility to carry out real system control by control algorithms, which are programmed and running in Matlab. Commands providing DDE communication between PLC and Matlab were introduced in the main program flow chart diagram.

Results of the real hydraulic system control with digital PI control algorithms were presented in the end of paper. Besides using PID control algorithms my aim is also to verify algorithms of modern control theory on this system, for instance linear quadratic algorithm based on the state space model or predictive control algorithms, where the linear model of system, created by nonlinear differential equations linearization, will be used as a predictor. However, I also plan to obtain the linear model of system as a linear regression ARX model by experimental identification of real system.

My next aim is to use real hydraulic system in nonlinear predictive control algorithms with a neural network. The neural network will be trained on the basis of measured data from real hydraulic system and it will serve as nonlinear predictor.

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