ANNALS of Faculty Engineering Hunedoara
– International Journal of Engineering

Tome XII [2014] – Fascicule 3 [August]
ISSN: 1584-2673 [CD-Rom, online]

a free-access multidisciplinary publication
of the Faculty of Engineering Hunedoara

[1.] Jakub ČERKALA, [2.] Anna JADLOVSKÁ

METHODOLOGY FOR EXPERIMENTAL IDENTIFICATION OF THE LABORATORY HYDRAULIC SYSTEM

[1-2.]Faculty of Electrical Engineering and Informatics, Technical University of Košice, SLOVAKIA

Abstract: Experimental identification is an alternative to more frequently used analytical identification for determining the parameters of an identified system. In this article, an off-line experimental identification method is described, with its principles and used structures of stochastic regressive models ARX and ARMAX applied in real experiment of linear model parameter identification. Examined laboratory model is also introduced with its features and implementation in distributed control system of Department of Cybernetics and Artificial Intelligence at Faculty of Electrical Engineering and Informatics. The main topic of this article is methodology and procedure to carry out an experimental identification of a given model while focusing also on data used for identification. To validate the results of the identification usedin the design of feedback control, pole-placement controller synthesis is used and results of laboratory model control based experimentally gained parameters are shown as graphs.
Keywords: experimental identification, laboratory hydraulic system, stochastic regressive model, pole placement method, feedback control

1. INTRODUCTION

This article focuses on methodology of real laboratory hydraulic system model experimental identification, which is located at Department of Cybernetics and Artificial Intelligence at Faculty of Electrical Engineering and Informatics of Technical University in Kosice. It follows up the article on control of this model [9], where the synthesis of control design was based on hydraulic system deterministic model obtained using analytical identification. Furthermore, this article presents an alternative procedure for determining the parameters of a linear model and the implementation of the results of experimental identification in control design. At the same time, a modified approach to the control of the laboratory model [9] and communication-based DDE / OPC between the model and the workstation [10] is also presented. Results of control experiments in articles [9] and [10] are suitable for qualitative comparison of similar control algorithms for model obtained from experimental data.

2. STOCHASTIC REGRESSIVE MODELS WITH LINEAR STRUCTURE

Experimental identification uses the combination of deterministic and stochastic model of the system [12],[13] in a single structure referred as a stochastic regression model, shown in Figure 1, where the output $y(k)$ is the sum of outputs $y_u(k)$ of the deterministic and $y_z(z)$ stochastic part at constant sampling period k.

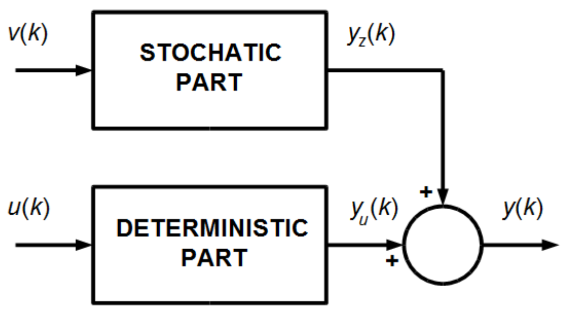

Figure 1: Stochastic regressive model of system

Deterministic part of the regressive model can be described as a discrete transfer function for linear dynamic system and its input is theexcitation signal $u(k)$. Stochastic part of the modeldescribes the dynamic properties of the filter, with the white noise as input - not measurable random signal $v(k)$ [2]. These transfer functions can be written in the general form

$$y(k) = z^{-d}\frac{B(z^{-1})}{A(z^{-1})}u(k) + \frac{C(z^{-1})}{A(z^{-1})D(z^{-1})}\nu(k)\ , \qquad (1)$$

where the$z^{-d}$is transport delay, $A(z^{-1})$ and $B(z^{-1})$ are polynomials of the deterministic part,polynomial$C(z^{1})$ is nominatorand product of polynomials $A(z^{-1})$ and$D(z^{-1})$ isdenominator of the stochastic part, $u(k)$ is excitation input signal and $\nu(k)$is vector of white noise.

The type of regressive model is determined by selected stochastic part of its transfer function. Model of an ARX (Auto-Regressive with eXogenous variable) type have nominator of stochastic partequal to 1 and the ARMAX(Auto-Regressive Moving Average with eXogenous variable) model type have nominator defined as polynomial$C(z^{-1})$.The ARMAX models are more suitable for modelling of systems with stochastic influences compared to ARX model type. Modifying the general stochastic model equation (1), it is possible to obtain equations of model outputs y_{arx} and y_{armax}

$$y_{arx}(k) = z^{-d}\frac{B(z^{-1})}{A(z^{-1})}u(k) + \frac{1}{A(z^{-1})}\nu(k), \quad y_{armax}(k) = z^{-d}\frac{B(z^{-1})}{A(z^{-1})}u(k) + \frac{C(z^{-1})}{A(z^{-1})}\nu(k), \qquad (2)$$

but in this case, for simplificationthe transport delay$d$is not taken into account for experimental identification.ARMAX model difference equations are expressed from model output equation (2):

$$\begin{aligned} y_{armax}(k) = &-a_1 y(k-1) - a_2 y(k-2) - \ldots - a_n y(k-n) + \\ &+ b_0 u(k-\nu) + b_1 u(k-\nu-1) + b_2 u(k-\nu-2) + \ldots + b_m u(k-\nu-m) + \nu(k) + \\ &+ c_0 \nu(k) + c_1 \nu(k-1) + c_2 \nu(k-2) + \ldots c_n \nu(k-n). \end{aligned} \qquad (3)$$

Calculation of linear structure model parameters is realized using the Least Square method, that belongs to regressive analysis methods group while the orders of stochastic regressive model polynomials depends on the order of identified system.

2.1. Laboratory model of hydraulic system construction and its properties

Laboratory model of hydraulic system is located at the Department of Cybernetics and Artificial Intelligence in Laboratory of Mechatronic Systems and it is suitable for experimental identification and real control experiments with fluids.

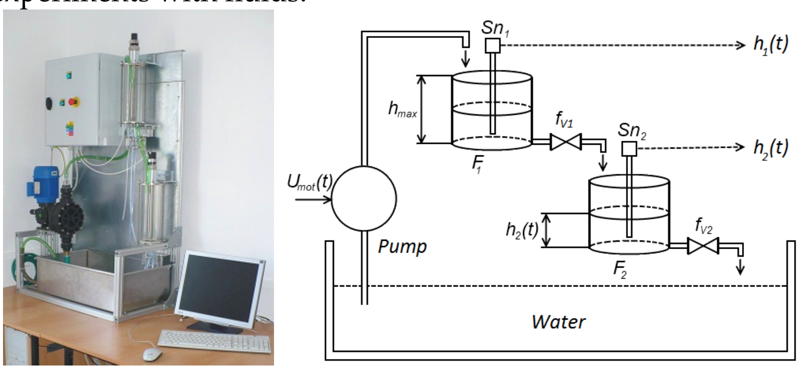

Figure 2: Laboratory model of Hydraulic system workstation and model concept scheme

Model is incorporated into the Distributed Control System of department as independent workstation connected into department’s industrial network. It is model of two opened cylindrical tanks, which are connected in series without interaction; workplace and conceptual scheme of the model are shown on Figure 2.

F_1 and F_2 are tank sections, f_{v1} and f_{v2} are sections of drain holes, $h_1(t)$ is fluid level in first tank, h_2(t) is fluid level in second tank, $U_{mot}(t)$ is voltage to the motor. Real laboratory model features the following properties:

- ✓ water serves as fluid, on the bottom of the model is water reservoir,
- ✓ water is pumped from the reservoir through the vane pump,
- ✓ water is pumped into top tank, from which it flows into lower through the valve, and then it flows back to reservoir

- ✓ tanks have four valves with different sections, that enable model configuration changes and adds options for simulating errors
- ✓ water level is scanned by capacitance sensors,
- ✓ pump motor is controlled via frequency converter,
- ✓ both tanks are same in size.

Vane pump [1] is implemented with an engine that is connected to the frequency convertor, which enables to achieve constant water flow at a constant voltage U_{mot}. The ratio of flow and voltage is linear and minimum flow without excitation voltage respectively the maximum possible flow into the first tankcan be adjusted, for the tank dimensions F_1 and F_{v1} that make sense.The capacitive fluid level sensors Dinel [7] are placed in the tank top, and because of that the water levels $h_1(t)$ and $h_2(t)$ on the bottom of the tank are unmeasurable, but this error does not affect the regulation, since it is outside the operating area. Capacitive sensors S_{n1}, S_{n2} and frequency convertorare connected on input/outputcard 1762 IF20F2 of Allen-Bradley [14] programmable logic controller (PLC). This PLCcan be programmed using personal computer (PC), which is a part of the workplace through the Ethernet connection RS Logix 500 programming environmentvia service program RS linx, which provides visibility of model's PLC in thedepartment Ethernet network.

2.2. Laboratory model and workstation capabilities

Matlab simulation language is used for the tasks of Experimental identification, as well as the RS Linx program that serves as DDE interface for communication and connection to model's PLC. The entire mechanism for collecting, storing and visualizing data as well as programs for the management and control is realized in the form of scripts and functions in Matlab.The PLC is operated by basic program that ensures the safety management as overflow checking, limiting of motor input voltage and so.This basic program in the PLC can be monitored respectively controlled in real time independently thought RS Logix 500 program, which among other things enables tracking variables in the graphical interface.

Part of the PLC and Matlab interconnection solution contains also the graphical user interface in Matlab realized as simple 2D plot, which enables plotting values of excitation signal $U_{mot}(t)$ andwater levels$h_1(t)$, $h_2(t)$ in real time, as well for measuring the values or for control and it refreshes it's data in each sampling period. Presented model features slow dynamics and sampling period T_s=1s is sufficient for model control. This communication subsystem is described in details in article[5]and[6].

3. METHODOLOGY OF EXPERIMENTAL IDENTIFICATION

- ✓ Step 1: a specific operating point is selected, against which the deviation of water level occurs, for example the water level in the middle of water tank.
- ✓ Step 2: the shape of excitation signal is determined by chosen operating point.
- ✓ Step 3: based on the physical construction of investigated device it is possible to estimate order of the stochastic regressive model used in identification and optimize the approximation of parameters for chosen model structure.
- ✓ Step 4: measurement of laboratory model response to excitation signal.
- ✓ Step 5: off-line experimental identification is based on measured data set, which is substantial in size to cover a wide behavior range of model in the operating area. In the calculation of dynamic system linear structure parameters are required both input and output data sampled with appropriate chosen sampling period.
- ✓ Step 6: identification, respectively calculation of parameters should be followed by verification of acquired deterministic model of linear structure to the investigated system. Appropriate method of validation is to compare the response of the original model and the approximated model for the same excitation signal, but for the part of the response data, which has not been used to determine the parameters of the approximated model.

In general, the deviation between the real and the approximated model should converge to a minimum. In case that the deviation of responses does not converge or is too large, model parameters of obtained approximation can be inaccurately estimated due to:

- ✓ insufficient order of system – order of real system was not adequately estimated,
- ✓ wrong type of regression model – the real system is affected by immeasurable signal that chosen type of regression model cannot filter out,
- ✓ data set was not large enough – parameters of obtained model and are not sufficiently robust to cover the whole working area,
- ✓ sampling period is too large – changes of values between the samples are too large.

4. TARGETS OF LABORATORY MODEL EXPERIMENTAL IDENTIFICATION

From the perspective of systemparameters experimental identification, the most important is its input, the excitation voltage $u_{in}(t)$ and its output, water level in second tank $h_2(t)$, because our task is to control it, illustrated at Fig.3. However, the water level in the first tank has to be taken into account in preparation of experiments.

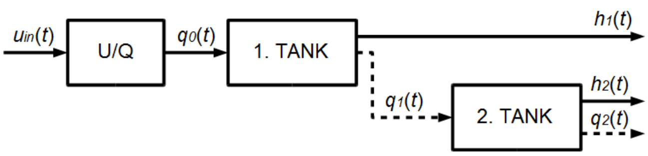

Figure 3: Block diagram of the laboratory model of hydraulic system

Experimental identification objective is to estimate the parameters in polynomials $A(z^{-1})$ and $B(z^{-1})$ of the delta model $G_{delta}(z^{-1})$in specific operating point.

$$G_{delta}(z^{-1}) = \frac{\Delta H_2(z^{-1})}{\Delta U_{in}(z^{-1})} = \frac{B(z^{-1})}{A(z^{-1})} \qquad (4)$$

Obtained linear delta transfer$G_{delta}(z^{-1})$ represents the behaviour of investigated system against this specific operating point.

4.1. The procedure for obtaining suitable working data for experimental identification

The first step for the identification of model is to determine the operating point and the operating area around this point. If there is a nonlinear model of system available [4], it is possible to mathematically determine the steady-state water h_2^s in second tank at a given steady flow respectively voltage using the differential equations of that model [8]. As mentioned above, the selectedoperating point is the water level at the center of the second tank, and from of excitation signal is derived from this value. This procedure is not necessary; it is possible to replace it with experiment of gradualvoltage increasesto estimate the operating point.

After selection of operating point, in which the experimental identification will be carried out, the generating of excitation signal follows. Suitable type for such excitation signal is pseudo-random binary signal, composed of random changes between maximum and minimum, and this randomness has Gaussian probability distribution. The offset to the operating point have always the same value with changingsign and the magnitude of the offsetis within the operating area. The duration of maxima and minima may not be very short, since the dynamics of the identified model is slow and change in excitation is therefore reflected slower. It is also necessary to take into account the maximum safe period in which there is no leakage of the first tank, but it is possible to avoid this problem by choosing a smaller offset magnitude.

In presented experiment for obtaining the data suitable for experimental identification is assumed, that on the beginning of experiment there is no excitation to the pump motor and both tanks are empty. It is practical to add a constant step excitation with operating point voltage and for necessary long time, after which is model in steady-state at operating point.

The next step is the actual measurement of data on the model and storing them for further processing. After starting the experiment, the communication subsystem captures the data from water level sensors via PLC. If there was no water leak in first tank and water level in second tank was moving within operational area, captured data should be suitable for experimental identification.

Experiment for measuring and saving laboratory model experimental identification data will provide a dataset consisting of an excitation data and adequate response data.

The first necessary adjustment to data sets is the removal of rise to the operating point, as it is not interesting for experimental identification, but it is still possible to use it in comparison oflinear structure of approximated model and laboratory model. The next step is the standardization of data, which removes the constant values of excitation and water level according to the selected operating point. The resulting excitation signal is a sequence of changing 1 and -1 associated with the relevant water level differenceagainst 0 and this ensures that the output will be in delta transfer function. The final step of the data preprocessing is splitting dataset into two parts, the first part are training data for experimental identification and the second are testingdata for validation of approximated linear structure model. Dataset after splitting is depicted.

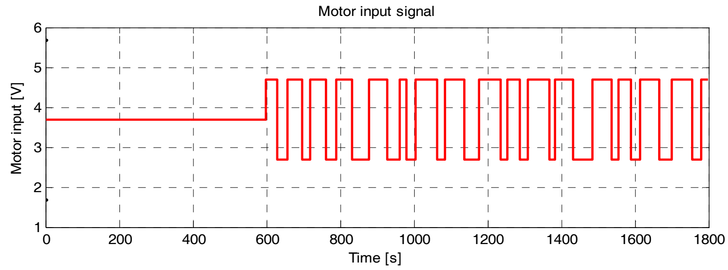

Figure 6: Pseudo-binary signal with constant

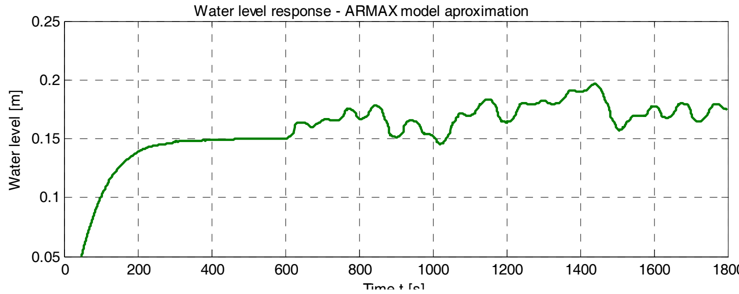

Figure 6: Water level in second tank – model response data

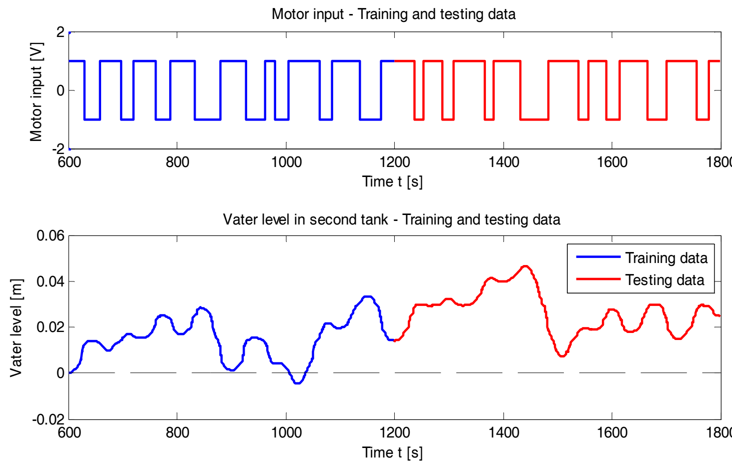

Figure 6: Preprocessed data set for experimental identification

4.2. Software tools for laboratory model experimental identification

For experimental identification purposes, a simulation language Matlab is used with its System Identification Toolbox that offers three approaches to experimental identification [11], which will be briefly presented:

From the perspective of a new System Identification Toolbox user, a dedicated graphics interface IDDENT tool, illustrated in Figure 7 is the best choice. Its main advantage is that it includes data preprocessing options as well as all toolbox functionality in one tool. However, this tool cannot be fully integrated into the master systemof laboratory model control.

Another specific procedure for an experimental identification is possible in Simulink, where the System Identification Toolbox has a special blockset for estimating the model parameters at the chosen structure, which can be adjusted as needed. On-lineexperimental identification algorithm is used and therefore it does not have applicationin this article.

Given that the main aim is to link the experimental identification with the control system of the laboratory model, the most appropriate way is to work directly with single Matlab functions, what eliminates the limitations of predefined objects. Functions for model parameters calculation require dataset of measured excitation and response signal along with selected orders of model approximation. For easier working with the datasets there is also an IDDATA object, which may contain important data and additional information such as physical variables or comments, making it easier to manage multiple datasets.

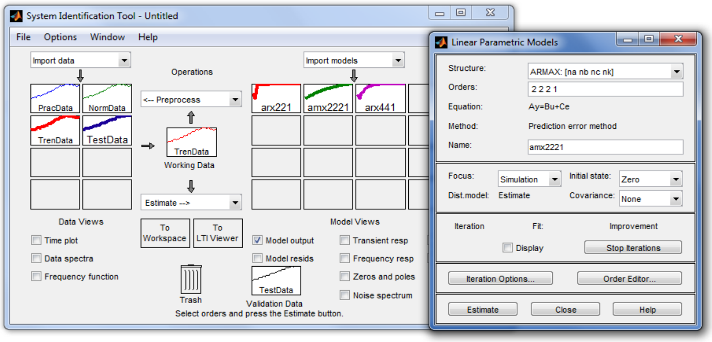

Figure 7: Experimental identification task using the IDENT tool

4.3. Experimental identification of laboratory model results and summary

After calculating the laboratory model of hydraulic system linear structure parameters, a model polynomials $A(z^{-1})$ and$B(z^{-1})$ are obtained for delta transfer function (5)

$$G_{aprox}(z^{-1}) = \frac{\Delta H_2(z^{-1})}{\Delta U_{in}(z^{-1})} = \frac{B_{armax}(z^{-1})}{A_{armax}(z^{-1})} \quad . \tag{5}$$

The resulting delta transfer approximation model is linear and can be used in the synthesis of the controller. However, it is important to verify that the transfer function with the estimated parameters corresponds to real model of the hydraulic system; it is possible to use the previously mentioned testing data. In general, the model with the estimated parameters should have the same response to the same excitation signal as investigated hydraulic system. Figure 8 demonstrates the results of an ARX (na = 2, nb = 2, nc = 1) and ARMAX (na = 2, nb = 2, nc = 2, nk = 1) model approximations. It is obvious that the ARX model is not suitable for the synthesis of control because it is unable to sufficiently approximate the laboratory hydraulic system. On the other hand, the ARMAX model can sufficiently minimize the deviation of water level in the second tank and therefore it can be used in the design of feedback control algorithms [3].

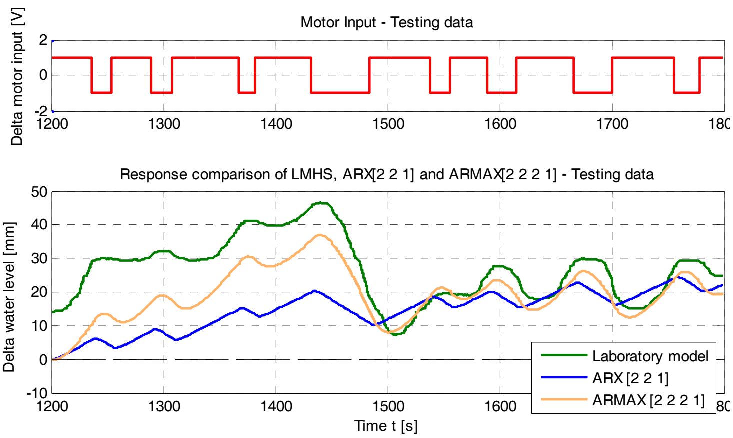

Figure 8: Comparison of ARX and ARMAX models response model to response of laboratory HS

4.4. Practical feedback control experiments on laboratory model

Results of laboratory model of hydraulic systemexperimental identification are used in the design of feedback control, which concept is illustrated in the block diagram, wherey(k) is the process value, $w(k)$ is desired process value, $e(k)$ is difference between actual and desired process value, $z(k)$ is unmeasurable errorand $u(k)$ is control action.The role of the regulator is to minimize $e(k)$ by control actioncalculated according to the law defined by controller parameters at each sampling period. Chosen feedback controller is the polynomial controller based on pole-placement method,

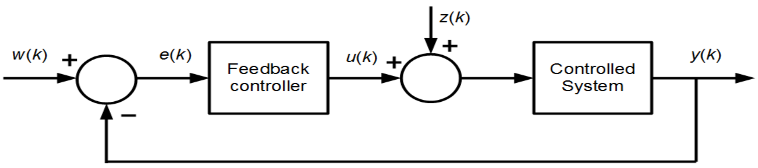

Figure 9: Basic feedback control loop

where selected poles define the behaviour of system in closed loop [2]. Transfer function of controlled system (6) is defined by polynomials $A(z^{-1})$ and $B(z^{-1})$, that were obtained by estimation.

$$G_p(z^{-1}) = \frac{Y(z^{-1})}{U(z^{-1})} = \frac{B(z^{-1})}{A(z^{-1})} = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \quad , \tag{6}$$

andcontroller (7) is defined by polynomials$Q(z^{-1})$ a $P(z^{-1})$ can be written in the form

$$G_R(z^{-1}) = \frac{U(z^{-1})}{E(z^{-1})} = \frac{Q(z^{-1})}{P(z^{-1})} = \frac{q_0 + q_1 z^{-1} + q_2 z^{-2}}{(1+z^{-1})(1+\gamma z^{-1})} \quad . \tag{7}$$

Closed loop control transfer function$G_w(z)$can be defined as

$$G_w(z) = \frac{Y(z^{-1})}{W(z^{-1})} = \frac{B(z^{-1})Q(z^{-1})}{A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1})}, \tag{8}$$

Denominator of closed loop control transfer function$G_w(z)$ is its characteristic polynomial $D(z^{-1})$

$$D(z^{-1}) = A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1}) \tag{9}$$

andrequired characteristic polynomial with chosen poles can be expressed as

$$D_z(z^{-1}) = 1 + \sum_{i=1}^{n_d} d_i z^{-i} \ , \quad n_d \le 4 \quad . \tag{10}$$

In equation (11) for polynomial equality

$$\underbrace{A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1})}_{D(z^{-1})} = D_z(z^{-1}) \tag{11}$$

is given specified layout of four poles of the transfer function, which can be achieved by appropriate choice of controller parameters (7) that are solution of equation (11). A system of equations with four unknown variablesq_0, q_1, q_2 and γ arises and it is convenient to write them in matrix form

$$\begin{bmatrix} b_1 & 0 & 0 & 1 \\ b_2 & b_1 & 0 & a_1 - 1 \\ 0 & b_2 & b_1 & a_2 - a_1 \\ 0 & 0 & b_2 & -a_2 \end{bmatrix} \cdot \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ \gamma \end{bmatrix} = \begin{bmatrix} d_1 + 1 - a_1 \\ d_2 + a_1 - a_2 \\ a_2 \\ 0 \end{bmatrix} \quad . \tag{12}$$

For parameters of ARMAX linear structure model (6) and four chosen poles it is possible to calculate the controller parametersq_0, q_1,$q_2$and γ and obtain the control action (13)

$$u(k) = q_0 e(k) + q_1 e(k-1) + q_2 e(k-2) + (1-\gamma)u(k-1) + \gamma u(k-2) \, . \tag{13}$$

Designed polynomial controller is applicable in control according to reference trajectory close to original operation point or to steady state control, where it minimizes errors and disturbances acting on the system at the operating point. Control of the laboratory model according to the reference trajectory with use of delta polynomial controller whose parameters were calculated from ARMAX model linear structure is depicted on Figure 10.

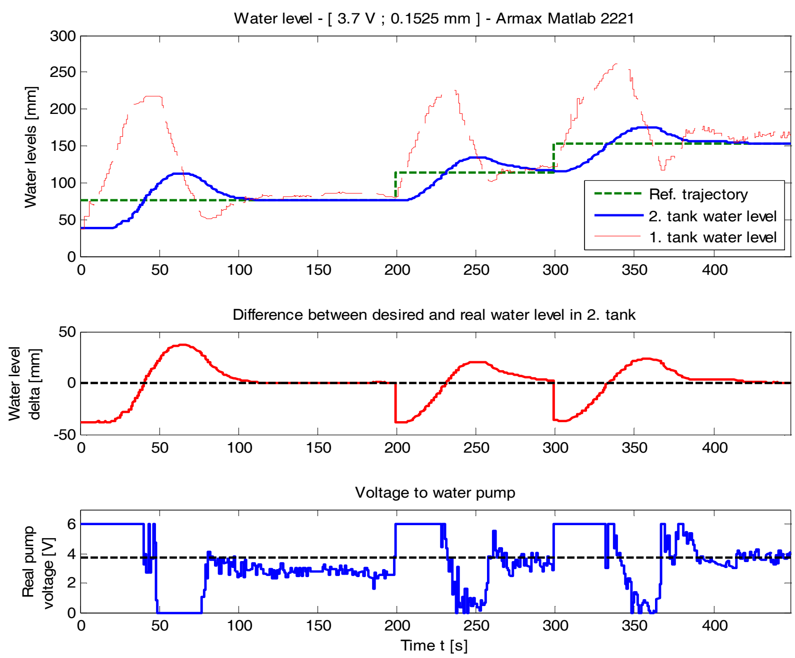

Figure 10: Real laboratory control experiment with ARMAX model used for controller synthesis

Control with pole-placement synthesis controller for linear structure ARMAX model with parameters estimated using experimental identification is applicable on real laboratory model of hydraulic system where the response of control actions can be influenced by appropriate selection of poles.

5. CONCLUSION

As demonstrated in this article, experimental identification is applicable on real model and results of identification can be implemented to control algorithms, what was illustrated on practical example, because in this way it is possible to design a controller based onapproximation of real system for appropriate type of regression model. Results and quality of laboratory model control are comparable to results presented in article [10], where parameters of analytical model were used the controller design.

Presented model have potential for wide spectrum of application in education process, namely in our subjects Control and Artificial Intelligence or Optimal and Nonlinear Systems from the viewpoint of broad range of usable methods, for example, an advanced control methods, such as state control or predictive GPC, MPC control were successfully implemented to laboratory model.

Acknowledgements

This work has been supported by the Scientific Grant Agencyof Slovak Republicunder project Vega No.1/0286/11 Dynamic Hybrid Architectures of the Multiagent Network Control Systems (50%), by the Research and Development Operational Program forproject: University Science Park Technicom for innovative applications with knowledge technology support, ITMS code 26220220182, co-financed by the ERDF (30%) and project KEGA 021TUKE-4/2012 (20%).

REFERENCES

[1] Bia-Verder, *SPRING membrane design*, technical documentation,(in Czech)
[2] BOBÁL, V., BÖHM, R.PROKOP and J. FESSL: *Practical aspects of self-tuning controllers: Algorithms and Implementation*, 1. Issue, Brno: VUTIUM, 1999, ISBN 80-214-12299-2, (in Czech)
[3] ČERKALA, J.: Application of Experimental Identification Results in Design of Control Algorithms for Model of Real Hydraulic System,*Masterthesis* (supervisor: doc. Ing. Anna Jadlovská, PhD), Košice: Faculty of Electrical Engineering and Informatics, Technical University in Kosice, 2012, p. 83, (in Slovak)
[4] ČERKALA, J. and A. JADLOVSKÁ: System Identification Toolbox Application in Experimental Identification of Linear Dynamical Systems. In: *Electrical Engineering and Informatics: Proceeding of the Faculty of Electrical Engineering and Informatics of the Technical University of Košice*: September, 2010, Košice, Slovak Republic. - Košice: TU, 2010 pp. 540-545, ISBN 978-80-553-0460-1, (in Slovak)
[5] ČERKALA, J. and A. JADLOVSKÁ: Application use of Matlab-DDE communication with multi-program approach and real-time plotting for identification and process control of laboratory model. In: *20th Annual Conference Proceedings of the International Scientific Conference - Technical Computing Bratislava 2012*, Hotel Sorea Regia, Bratislava, 7. November 2012, www.posterus.sk/tcb2012, CD-ROM, 8 p, ISBN 978-80-970519-4-5, (in Slovak)
[6] ČERKALA, J. and A. JADLOVSKÁ: Experimental identification of nonlinear dynamic system using IDENT Tool in Matlab environment. In: *Electrical Engineering and Informatics 3: proceeding of the Faculty of Electrical Engineering and Informatics of the Technical University of Košice*. - Košice: FEEI TU, 2012 pp. 46-51, ISBN 978-80-553-0890-6, (in Slovak)
[7] *Dinel, Capacitance level sensors CLM-36*, User's manual, (in Czech)
[8] FIKAR, M. and J. MIKLEŠ:*System identification*. STU publishers, Bratislava, 1999, ISBN 80-227-1177-2 (in Czech)
[9] JAJČIŠIN, Š. and A. JADLOVSKÁ: Control of the Laboratory Model of Hydraulic System. In: *Electroscope – online journal for Electrotechnics*, Vol. 2011, No. III, ISSN 1802-4564, (in Slovak)
[10] JAJČIŠIN, Š.: Verification of Control Algorithms with DDE Communication on Real Hydraulic System. In: *SCYR 2011: 11th Scientific Conference of Young Researchers of Faculty of Electrical Engineering and Informatics Technical University of Košice*: proc. – Košice, FEEI TU, 2011,pp. 388-391, ISBN 978-80-553-0644-5, (In Slovak)
[11] LJUNG, L.: *System Identification Toolbox*, User's manual, 6. Version
[12] MODRLÁK, O.: *Introduction to discrete parametric identification*, Liberec, Materials for study, 2004, (in Czech)
[13] NOSKIEVIČ, P.: System modelling and Identification. Ostrava : Montanex a. s. 1999, 276 p., ISBN 80-7225-030-2, (in Czech)
[14] Rockwell Automation, *Allen-Bradley PowerFlex 40 Adjustable Frequency AC Drive*, User's Manual.