A Simple Hydraulic System as a Laboratory Equipment for Demostrating On-Off Control

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Abstract – **This paper deals with a didactic water tank system which is the interesting equipment for demonstration many control problem solutions. In order to stimulate future research, after short description of the system modelling and control strategy, some experimental results are presented. The evaluation of the impact of experimental work on student learning is planned.**

Keywords – **Industrial automation, Two-position controller, Lab equipment, Engineering education.**

I. INTRODUCTION

Many industrial control systems have approximately first order dynamics and are controlled simply by switching an actuator *on* and *off*. Liquid level control systems and heating processes are examples of such systems [1]. The principal advantage of on-off control is that it is a cheap control solution, where the applied controller and the actuator are usually inexpensive. Moreover, on-off control does not even require a controller as the control function can be created with contacts and relays, or other such devices.

The main drawback of the two-position controller implementation is that its normal mode is constant cycling. In addition, the switching rate of two-position controller, as well as the oscillation amplitude of controlled variable is influenced directly by hysteresis present in the real on-off controllers. Therefore, a compromise between the lifetime of the actuator and the accuracy of control is the only possible solution.

The paper is organized as follows. Section 2 introduces some preliminary facts before the experimental setup is presented. The description of the experimental environment is summarized in Section III and illustrated by experimental results. Finally some conclusions of the work are presented in Section IV.

II. A REVISIT TO ON-OFF LIQUID LEVEL CONTROL

In this section, some assumptions are made for the object to be modeled, and a control approach is considered.

A. Tank System Model

A cylindrical reservoir shown in Fig. 1, with cross section A and outlet area s, has an influx Q_{in} and an outflux Q_{out}. Note that due to the assumption of an ideal fluid, all forces acting on the fluid are conservative and thus there is an exchange between potential and kinetic energy. Moreover, the outlet area is small in comparison to the cross section of the tank, and as Torricelli's law states, the efflux rate is given by $v_{\text{out}} = \sqrt{2gh}$, where g is the acceleration due to gravity and h is the height of liquid in the tank.

Considering mass balance, the liquid volume change is given by

$$A\dot{h} = Q_{\text{in}} - Q_{\text{out}}, \tag{1}$$

where $Q_{\text{out}} = s\sqrt{2gh}$, and the model differential equation becomes

$$\dot{h} + \frac{s}{A}\sqrt{2gh} = \frac{1}{A}Q_{\text{in}}. \tag{2}$$

Let the influx be constant $Q_{\text{in}} = Q_{\text{in}}^0$. Equating fluxes $Q_{\text{out}}^0 = Q_{\text{in}}^0$, the stationary point h^0 can be calculated by letting $\dot{h} = 0$, which yields

$$h^0 = \frac{1}{2g}\left(\frac{Q_{\text{in}}^0}{s}\right)^2 \tag{3}$$

State space representation of the dependence of the influx Q_{in} on the outflux Q_{out} becomes

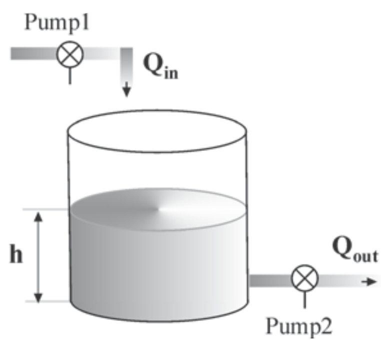

Fig. 1. A cylindrical water tank

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$$\dot{h} = -\frac{s}{A}\sqrt{2gh} + \frac{1}{A}Q_{\text{in}} = f(h, Q_{\text{in}})$$
$$Q_{\text{out}} = s\sqrt{2gh} = g(h, Q_{\text{in}}) \quad . \tag{4}$$

The behavior of a nonlinear system near an operating (stationary) point can be described by the linear differential equation. Introducing variables which denote deviations from the operating point $\Delta h = h - h^0$, $\Delta Q_{\text{in}} = Q_{\text{in}} - Q_{\text{in}}^0$, and $\Delta Q_{\text{out}} = Q_{\text{out}} - Q_{\text{out}}^0$, the linear differential equation can be found as follows

with

$$\dot{\Delta h} = -\frac{s}{A}\sqrt{\frac{g}{2h^0}}\Delta h + \frac{1}{A}\Delta Q_{\text{in}}$$
$$\Delta Q_{\text{out}} = s\sqrt{\frac{g}{2h^0}}\Delta h \quad . \tag{5}$$

The linear, time-invariant first order system, given by (5), describes how a perturbation ΔQ_{in} around the nominal input Q_{in}^0 causes a perturbation around the nominal state h^0.

B. First Order Linear System Subject to On-off Control Input

Fig. 2 shows the block diagram of the closed-loop system configuration with a two-position controller. Recall that a two-position controller recognizes only two states and has only two actions - ON or OFF. To reduce the switching rate, the two-position controller is equipped with hysteresis (dead band) which is a special differential gap between two states. It is well known that the type of controlled object plays an important role [2], [3].

There is no general method of designing control loop with non-linear controller. Configurations with two-position controllers are designed on a case-by-case basis. In this section, the attention will be paid to the behavior of a two-position controller in the system with a first order lag object which is in accordance with the previous analysis.

Let a single-input single-output linear control object in Fig. 2 be described by the differential equation

$$\dot{c}(t) = -ac(t) + K_{\text{ob}}\, a\, u(t)\,,\ a = 1/T_{\text{ob}} \tag{6}$$

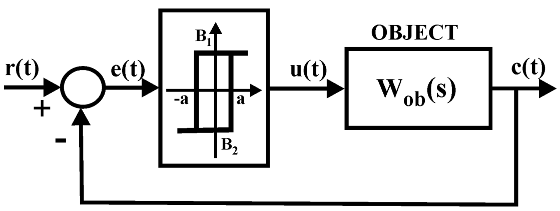

Fig. 2. Block diagram of the closed loop system with a two-position controller

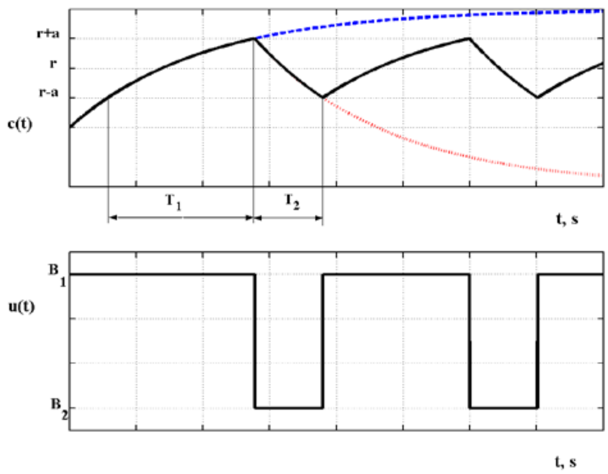

Fig. 3. Step response and object input for system in Fig. 2.

where K_{ob} and T_{ob} are static gain and time constant, respectively, $u(t)$ and $c(t)$ denote the control signal and output signal of the object. If there is switching hysteresis $(\pm a)$, two controller states are given by

$$u(t) = \begin{cases} B_1 > 0 & \text{for} \quad e > a \\ B_2 \le 0 & \text{for} \quad e < -a \ . \\ \text{remains unchanged } (B_1 \text{ or } B_2) & \text{for} \quad |e| < a \end{cases} \tag{7}$$

By integrating the differential equation (6) the output of the system $c(t)$ can be find as

$$c(t) = c(0)\,\mathrm{e}^{-t/T_{\text{ob}}} + \int_0^t \mathrm{e}^{-(t-\tau)/T_{\text{ob}}} K_{\text{ob}} u(\tau)\,\mathrm{d}\tau\,, \tag{8}$$

where $c(0)$ is the initial condition.

The essence of on-off control is to apply maximum or minimum control effort depending on the state of the system. The system never reaches a steady state r, but enters the regime of undamped oscillations around it, whose period may be determined by providing two boundary conditions, i.e.

$$c(t = T_1) = r + a = (r - a)\,\mathrm{e}^{-T_1/T_{\text{ob}}} + K_{\text{ob}} B_1 \left(1 - \mathrm{e}^{-T_1/T_{\text{ob}}}\right) \tag{9}$$

and

$$c(t = T_2) = r - a = (r + a)\,\mathrm{e}^{-T_2/T_{\text{ob}}} + K_{\text{ob}} B_2 \left(1 - \mathrm{e}^{-T_2/T_{\text{ob}}}\right). \tag{10}$$

The *on* period T_1 and the *off* period T_2, which are marked on the responses given in Fig. 3, are determined as follows

$$T_1 = T_{\text{ob}} \ln \frac{K_{\text{ob}} B_1 - r + a}{K_{\text{ob}} B_1 - r - a} \tag{11}$$

and

$$T_2 = T_{\text{ob}} \ln \frac{K_{\text{ob}} B_2 - r - a}{K_{\text{ob}} B_2 - r + a} \quad . \tag{12}$$

Note that the switching rate of two-position controller is influenced directly by hysteresis. From practical point of

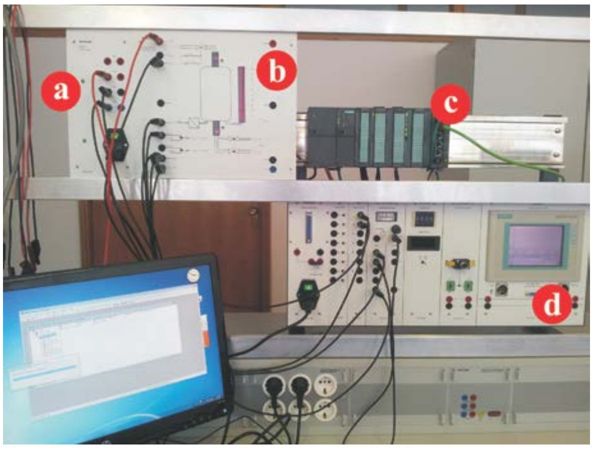

Fig. 4. Layout of the experimental environment

view, requirements for smaller amplitude and a greater period of oscillation are desirable. These are two contradictory requirements, and a compromise is the only possible solution.

III. Overview of Experimental Setup

This section discusses the equipment and experimental procedures used to prove the control strategy presented within this paper.

A. Description of the Experimental Environment

The solution of on-off tank filling control using two-position controller with hysteresis is presented [4], [5]. Experimental environment shown in Fig.4 consists of: (a) WUEKRO power supply unit which supplies the tank filling simulation with +/-15VDC; (b) WUEKRO tank filling simulator, which has an analogue level sensor that measures actual level and also gives the information on the current level. For better level visualization, it has light indication of the state of liquid in the tank. Besides the sensor, there are two valves used to empty tank at different discharge rates, placed on the pipes with different cross sections. The valve with smaller cross section (V2), and the valve for filling the tank (V1) are used in experimental consideration. These valves are controlled by binary signals, so they can take one of two final positions: opened or closed (0/24 VDC); (c) For the level control, a programmable logic controller (PLC) Siemens S7-300 is used. The CPU of this controller is 314F-2PN/DP, and it is connected with digital input/output module that has 16 digital inputs and 16 outputs, analogue input/output module that has 4 analogue inputs, and 2 analogue outputs, as well as the communication module CP 343-2; (d) The actual fluid level can be shown on the Siemens “Touch panel TP177B 6” which is otherwise used in applications with less complex systems.

The scheme of tank filling level is shown in Fig. 5 [5], [6]. The actual level value is presented with x, which is a process variable, appropriately measured by sensor and converted on a linear basis into a voltage signal U_{H} in the range from 0 to

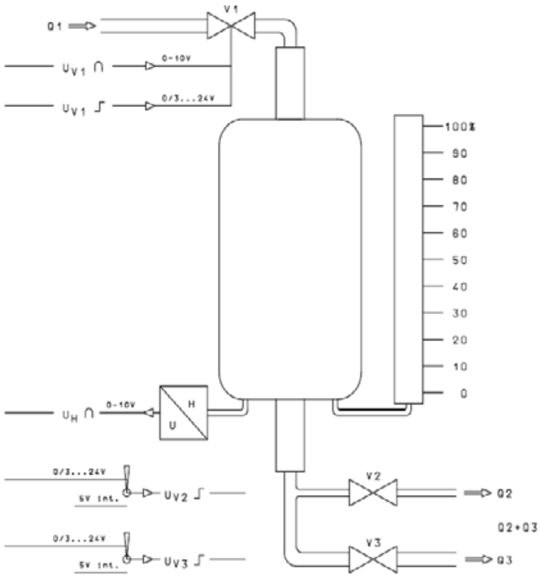

Fig. 5. Schematic representation of the reservoir with liquid [5]

10V. Accordingly, a filling level of 50% corresponds to a voltage of 5V at output U_{H}.

Setpoint value w is given also as analogue signal, and that is output of potentiometer which can be easily changed during the program execution. The potentiometer output is connected to the analogue input of PLC and it can be scaled during the program execution. It is very important to limit the setpoint value and keep it not to be higher than 10% and lower than 90% of the full scale. Due to the switching hysteresis, process variable x 'hunts' between upper response value $X_{\mathrm{o}} = (w + 10)\%$ and lower response value $X_{\mathrm{u}} = (w - 10)\%$. Difference between the upper response value and lower response value is called the switching difference X_{s}.

Reading the task, it is clear that PLC gets two analogue signals at its analogue input module. One of them gives the information on the actual fluid level, and the other on the setpoint value (and pursuant to it, the limits within which a fluid can be calculated). These analogue signals x (current level of liquid in the tank) and w (given level) are in the range between 0 and 100%. However, the analogue input module of S7-300 converts these signals into numerical values in the range from 0 to 27648 or from -27648 to 27648,

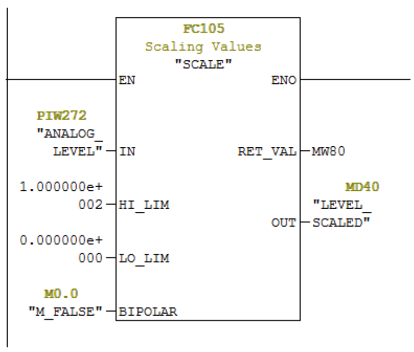

Fig. 6. “SCALE” block in ladder diagram

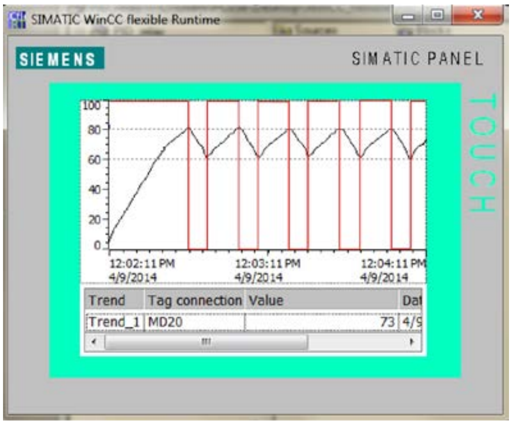

Fig. 7. Changing fluid level if lower and higher response values are 60% i 80% (black line); Valve V1 is opened while level is rising, and closed while level is falling (red line)

depending on binary value of signal at the "BIPOLAR" input of scaling block [7].
Scaling block “SCALE” is SIMATIC function FC 105 from “Standard Library”. In this case, the “BIPOLAR” input is set to “0” (logical zero), so the signal is converted in a numerical value in the range from 0 to 27648. The analogue signal x is the input of one “SCALE” block, and w is the input of another “SCALE” block. At the inputs “HI_LIM” and “LO_LIM” of scale blocks limits are written (in the form of a real number) within which the input analogue signal should be observed, in the case the limits are 0 and 100. The scaled value is written in the memory variable of double word type, in this case the address of first “SCALE” block output is MD40, and the address of the other “SCALE” block output is MD48. If programing is performed in the ladder diagram, the “SCALE” block is as shown in Fig. 6.

Having in mind that control signal is digital, or binary (it can only have the values of 0 and 1), the value of memory word MD40 (which is the scaled value of input variable x) is compared to the lower response value. If the valve V1 is open, the corresponding digital output is set and the tank is filled with fluid. When variable x becomes bigger than upper response value, valve V1 closes, and the corresponding digital output is reset. Controlling the valve V2 is similar. If the actual fluid level is lower than lower response value, the valve V2 closes, which means that the corresponding digital output is reset. Likewise, if actual fluid level is higher than upper response value, the valve V2 opens, which means that corresponding digital output is set. Note that lower and upper response values are changed at the same time as analogue input variable w.

B. Results of Experiment

Fig. 7 shows the changes of fluid level if setpoint value is 70%, which means that lower and upper response values are 60% and 80%, respectively. In Fig. 7 also can be seen if valve V1 (fluid inflow) is opened or closed (red line). It is obvious that inflow rate is smaller than discharge rate, while period of filling tank in given range is shorter than period of emptying tank in same range. The period of filling tank from 60% to 80% is about 12s, while the emptying period is about 7s.

It can be noticed that while the level is rising and falling the line that shows actual value is not smooth, but has some deviations, which is due to the sample time of data acquisition (500ms), and due to fact that actual value of liquid level in the tank is presented in integer format.

C. Evaluation of Student Learning

In addition to the official faculty teaching evaluation for the courses related to the topic, at the end of each semester anonymous student surveys will be conducted to determine whether the learning outcomes have been successfully achieved. A proposal for evaluating the impact of the experimental work on student learning has been prepared.

IV. CONCLUSION

This paper describes the control of fluid level in tank using controller with hysteresis. As tank simulator WUEKRO simulator is used. This is a part of the equipment at the Faculty of Electrical Engineering, University of East Sarajevo. By using the PLC Siemens S7–300 a simple controller structure is realized. The behavior of process is monitored on Siemens Touch panel. Using this simulator, students become familiar with PLC programming, as well as with process control. In this paper the control of fluid level in tank using controller with hysteresis is presented, but this tank can also be controlled with PI/PID controller, which gives space for further work with this simulator and its use in education.

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REFERENCES

[1] F.G. Shinskey, *Process Control Systems: Theory for the User*, Prentice Hall, 1999.
[2] B. Matić, *Design of Automatic Regulation and Control of Technological Processes*, Svjetlost, OOUR Zavod za udžbenike i nastavna sredstva, Sarajevo, 1989 (in Serbian).
[3] Č. Milosavljević, *Linear and Nonlinear Automatic Control Continuous-time Systems*, Faculty of Electrical Engineering, East Sarajevo, 2007 (in Serbian). (http://www.etf.unssa.rs.ba/download/TAU_2.pdf)
[4] M. Ristović, S. Lubura, "Fluid Level Control in Tank using Programmable Logic Controller Siemens S7-300", Infoteh®-Jahorina 2014, Conference Proceedings, pp. 1051-1056, Jahorina, Republic of Srpska, B&H, 2014 (in Serbian). http://www.infoteh.rs.ba/zbornik/2014/radovi/SUP/SUP-6.pdf
[5] "Experimental Manual V174 – Digital Control 1 with SIMATIC S7", WUEKRO GmbH
[6] "Experimental Manual V175 – Digital Control 2 with SIMATIC S7", WUEKRO GmbH
[7] "Experimental Manual V173 – Programmable Logic Controllers – SIMATIC S7-300", WUEKRO GmbH