Additive Faults Detection and Level Control in Coupled Tanks

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Abstract: - This paper presents a strategy for level control, detection and localization of the possible faults types for coupled tanks. The control and faults detection algorithm was developed using the combination of Matlab - Simulink with WinCon 5.1 software. Also in the paper, a mathematical model of the process is developed used design and control algorithm. The experimental applications were developed on the didactical plant ”Quanser Water Level Control Two Tank Module”.

Key-Words: - Detection, localisation, additive faults, disturbances, noise, level control, pole placement.

1 Introduction

Fault is a deviation from the normal behaviour in the plant or its instrumentation. We are concerned with the detection and diagnosis of faults in an engineering system, whether they occur in the plant or in its measurement and control instruments (sensors and actuators) [4].

This paper presents the situations when possible faults, disturbances and noises appear in the didactical plant for level control that uses the coupled tanks ”Quanser Water Level Control Two Tank Module” and was developed for tank 1 and tank 2 level controller design using pole placement method.

The fault detection and the diagnosis system implement the following steps: fault detection, that is, the indication that something is going wrong in the monitored system; fault isolation, that is, the determination of the precise location of the fault and fault identification, that is, the determination of the magnitude of the fault [1].

The detection function is indispensable and the isolation function is usually also required. The combination of isolation and identification is also referred to as diagnosis.

The detection and isolation functions may be performed sequentially, that is, by invoking the isolation function only once a fault has been detected, or in parallel, that is, simultaneously [4].

In practical situations, fault diagnosis needs to be performed in the presence of disturbances, noise and modelling errors.

Therefore the diagnostic algorithm needs to be designed that it: is made insensitive to the disturbances; it includes mechanisms to suppress the effects of noise; it's robust with respect to modelling errors; maintains sufficient sensitivity with respect to faults.

2 Additive faults and disturbances

Additive process faults are unknown inputs acting on the plant, which are normally zero and which, when present, because a change in the plant outputs independent of the known inputs. Such faults best describe plant leaks, loads, etc [1].

Additive faults and disturbances will be handled as unspecified deterministic functions of time. Noises are unknown extra inputs, just like the additive disturbances, but they are assumed to exhibit random behaviour.

They are also assumed to have zero mean; any nonzero mean can be handled as a separate disturbance. The noises are also nuisance variables the effects of which need to be suppressed. Modelling errors are errors or uncertainties in the parameters of the monitored system.

They are discrepancies between the true system and the model – but they represent an undesirable interference with fault diagnosis. A disturbance is also an unknown extra input acting on the plant. Thus physically there is no difference between a disturbance and certain additive faults.

We consider as faults those extra inputs the presence of which we wish to detect while we consider as disturbances those which we want to ignore and be unaffected by [1].

We consider a system with multiple inputs:

$$u(t) = [u_1(t).......u_k(t)]' \quad (1)$$

and multiple outputs:

$$y(t) = [y_1(t).......y_\mu(t)]' \quad (2)$$

For a linear discrete dynamic system, the nominal input-output relationship (without faults, disturbances and noise) is:

$$y(t) = M(\phi)u(t) \quad (3)$$

Assume that a subset $u_c(t)$ of the inputs is controlled while the rest, $u_M(t)$, are measured.

2.1 Additive faults

We considered first the faults; in this generic system, the following additive faults are possible: input actuator faults $\Delta u_C(t)$, input sensor faults $\Delta u_M(t)$, plant faults $\Delta u_P(t)$, output sensor faults $\Delta y(t)$ (see figure 1) [1].

The observed variables $u_c(t)$, $u_M(t)$ and y (t) are related to the actual plant inputs $u_C^\circ(t)$ and $u_M^\circ(t)$ and the actual plant output $y^\circ(t)$.

$$u_C^\circ(t) = u_C(t) + \Delta u_C(t) \quad (4)$$

$$y^\circ(t) = y(t) - \Delta y(t) \quad (5)$$

$$u_M^\circ(t) = u_M(t) - \Delta u_M(t) \quad (6)$$

The nominal relationship (3) is valid between $u_C^\circ(t)$, $u_M^\circ(t)$ and $y^\circ(t)$, with the additional input $\Delta u_P(t)$, where $u_C^\circ(t)$, $u_M^\circ(t)$ is true value of $u_C(t)$, $u_M(t)$.

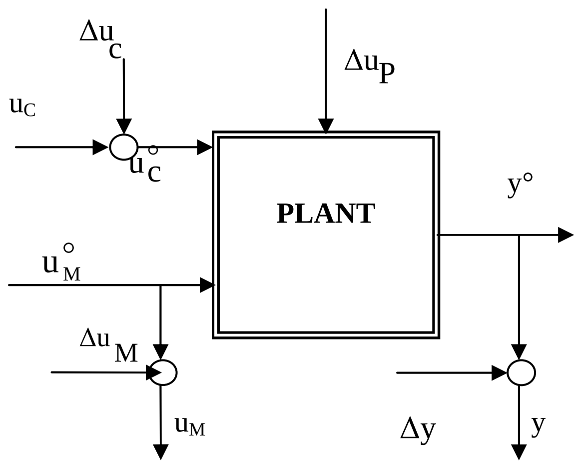

Fig.1 Additive faults

Write: $u(t) = \begin{bmatrix} u_C(t) \\ u_M(t) \end{bmatrix}$

$$M(\phi) = [M_C(\phi) | M_M(\phi)] \quad (7)$$

Thus the input-output relationship for the system with faults is:

$$\begin{aligned} y(t) - \Delta y(t) &= [M_C(\phi) | M_M(\phi)] \begin{bmatrix} u_C(t) + \Delta u_C(t) \\ u_M(t) - \Delta u_M(t) \end{bmatrix} + \\ &+ H_{PF}(\phi)\Delta u_P(t) = M(\phi)u(t) + M_C(\phi)\Delta u_C(t) - \quad (8) \\ &- M_M(\phi)\Delta u_M(t) + H_{PF}(\phi)\Delta u_P(t) \end{aligned}$$

where $H_{PF}(\phi)$ is the plant-fault transfer function, $\Delta y(t)$ is the fault associated with y(t), Δu_C is the fault associated with u(t), ϕ is the shift operator. Equation (8) can be written as:

$$y(t) = M(\phi)u(t) + H_F(\phi)p(t) \quad (9)$$

where $p(t)$ is the combined vector of additive faults:

$$p(t) = \left[\Delta u_C'(t) | - \Delta u_M'(t) | \Delta u_p'(t) | \Delta y'(t)\right]' \quad (10)$$

and $H_F(\phi)$ is the combined fault transfer function

$$H_F(\phi) = [M_C(\phi) | M_M(\phi) | H_{PF}(\phi) | I] \quad (11)$$

2.2 Additive disturbances and noise

Now consider the additive disturbances and noises and temporarily ignore the faults. The additive disturbances $q(t)$ act on the plant (see figure 2).

The following noises are possible: input actuator noise $\delta u_C(t)$, input sensor noise $\delta u_M(t)$, plant noise $\delta u_p(t)$, output sensor noise $\delta y(t)$ [1].

Then:

$$u_C^\circ(t) = u_C(t) + \delta u_C(t) \quad (12)$$

$$y^\circ(t) = y(t) - \delta y(t) \quad (13)$$

$$u_M^\circ(t) = u_M(t) - \delta u_M(t) \quad (14)$$

$$y(t) = M(\phi)u(t) + H_D(\phi)q(t) + H_N(\phi)v(t) \quad (15)$$

where v(t) is the combined vector of additive noises, $\delta y(t)$ is the noise associated with y(t), $\delta u(t)$ is the noise associated with u(t).

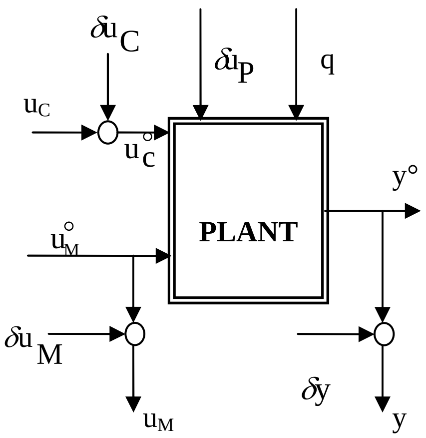

Fig.2 Additive disturbances and noises

$$p(t)=\left[\delta u_C^{'}(t)\middle|-\delta u_M^{'}(t)\middle|\delta u_p^{'}(t)\middle|\delta y^{'}(t)\right]^{'} \quad (16)$$

$H_D(\phi)$ is the disturbance transfer function, $H_N(\phi)$ is the combined noise transfer function (with $H_{PN}(\phi)$ denoting the plant-noise transfer function):

$$H_N(\phi)=\left[M_C(\phi)\middle|M_M(\phi)\middle|H_{PN}(\phi)\middle|I\right] \quad (17)$$

Finally, if additive faults, disturbances and noise are simultaneously present, which is normally the case, and then the input-output relationship becomes:

$$y(t)=M(\phi)u(t)+H_F(\phi)p(t)+H_D(\phi)q(t)+H_N(\phi)v(t) \quad (18)$$

3 Description of the didactical plant

3.1 Description of the plant

Didactical plant "Quanser Water Level Control Two Tank Module" consist of a pump with a water basin and two tanks of uniform cross sections (figure 3). Such an apparatus forms an autonomous closed recirculation system. The two tanks, mounted on the front plate, are configured such that the flow from the first tank flows into the second tank [6].

The flow from the second tank flows into the main water reservoir. In each one of the two tanks, liquid is withdrawn from the bottom through an outflow orifice. The outlet pressure is atmospheric.

Both outlet inserts are configurable and can be set by changing inserts that screw into the tapped holes at the bottom of each tank. In order to introduce a disturbance flow, the first tank is also equipped with a drain tap so that, when opened, flow can be released directly into the water basin.

We can see the technological diagram of the plant with tow tanks coupled presented in figure 4.

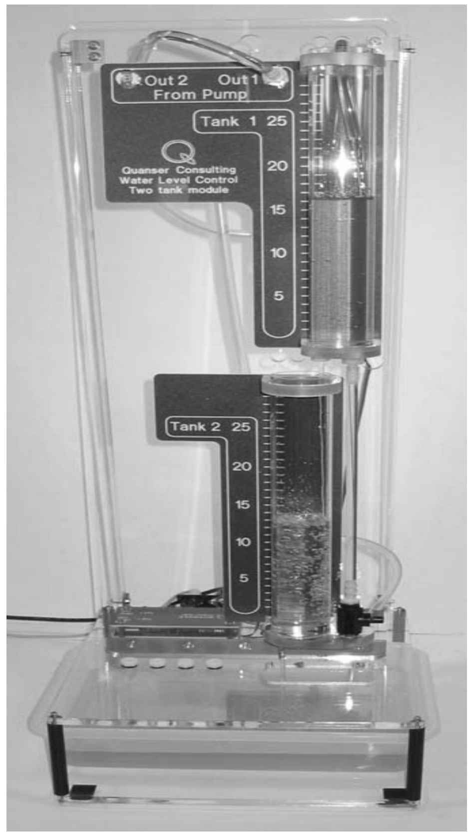

Fig.3 Didactical plant with coupled tanks

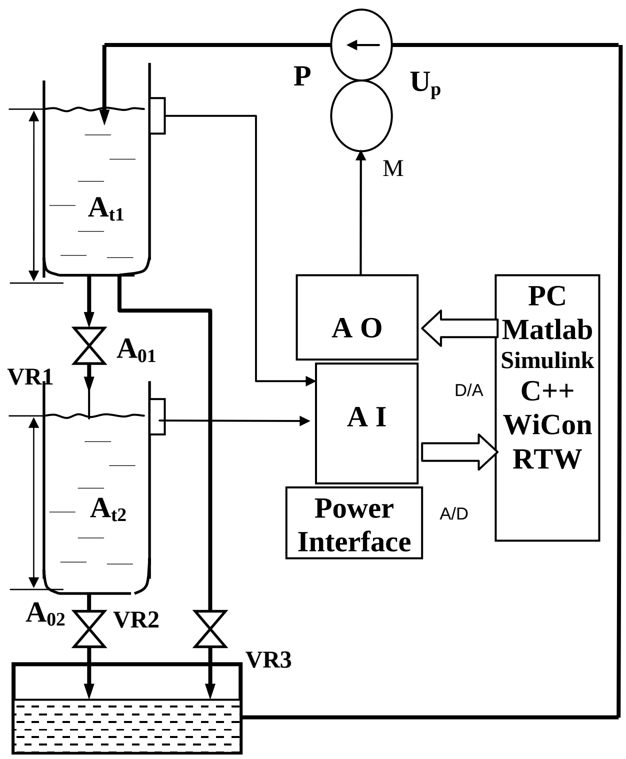

Fig.4 Technological diagram of the plant

where: $Tank_1$, $Tank_2$ - are the coupled tank of the plant, F_{i1}, F_{i2}, F_{o1}, F_{o2} are the volumetric inflow and outflow rate for tank 1 and tank 2, pump – the pump of the plant, M is the motor of the plant; U_g the voltage of the generator which applied un a square signal with a frequency 0,01 Hz and an amplitude: A= ±1 cm.

The two system variables are directly measured on the Coupled-Tanks rig by pressure sensors and available for feedback [6].

The water level in each tank is measured using a pressure-sensitive sensor located at the bottom of the tank. Additionally, a vertical scale is also placed beside each tank for a visual feedback of each tank's water level. The sensor output voltage increases proportionally to the applied pressure.

Calibration of each pressure sensor's offset and gain potentiometers is required to keep level measurement consist with type of liquid used in the coupled-tank experiment. The Coupled-Tank pump is a gear pump composed of a 12-Volt DC motor with heat radiating fins.

The equipments listed for this experiment include: a PC with a MultiQ-3 data acquisition card and a connecting board, the software environment: Windows, Matlab, Simulink, RTW and WinCon 5.1, the water tank apparatus with a water basin and a Universal Power Module UPM-2405.

3.2 Description of the components and software WinCon 5.1

To realise this experiment, the following hardware and software are required [2]:

- Power Module: Quanser UPM 2405 (figure 5).
- Data Acquisition Board: Quanser MultiQ PCI/ MQ3/Q8, NI-E (figure 6).
- Coupled-Tank Plant: Quanser Coupled Tanks, as represented in Figure 3.
- Real-Time Control Software: The WinCon-Simulink-RTX configuration.

The Universal Power Module contains:

- an input from analogue voltages of sensor adaptors that realise analogue digital conversion;
- an analogue output for pump DC-motor command; an analogue input from analogue output of data acquisition card;
- an analogue output to analogue input of data acquisition card.

It is necessary to make the following connexions with the data acquisition card installed on the PC:

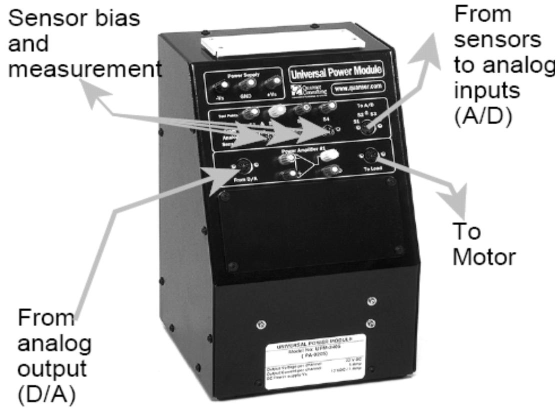

Fig.5 Universal Power Module

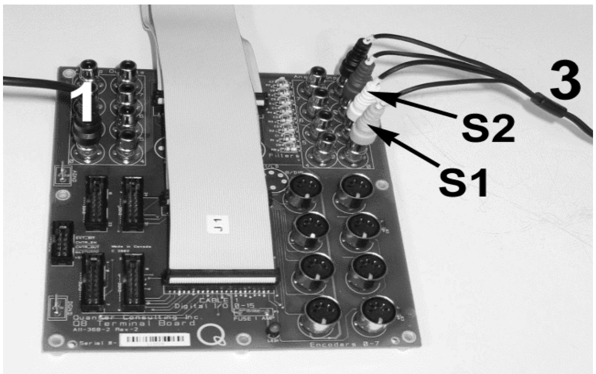

Fig.6 Quanser MultiQ PCI data acquisition

- connect the cable from the desired D/A channel(s) (for SISO systems) to the Power amplifier(s) input "From D/A";
- connect the output of the power amplifier to the actuator [motor(s)] of the main plant(s) using the supplied cable;
- connect the analogue sensor signals of the main plant to the Power Module "From Analogue Sensors" [6].
- connect the analogue sensor signals of the module to either the main plant secondary.

The pressure proportional water level voltage, measured on the UPM 2405 channel S_1 for tank 1 and on channel S_2, should be zero when than tank is empty, while it should be between 4 Volts and 4.2. Volts when the tank water level is at 25 centimetres.

The Q8 terminal board (figure 6) and the Universal Power Module (UPM-2405) (figure 5) are connected with the necessary cabling to interface to and use the Coupled – tank plant.

WinCon 5.1. software is a high performance real – time process software that runs on Windows XP application.

It allows running code generated from a real-time Simulink diagram on the same PC or on a remote PC.

The automatically generated real-time code constitutes a stand-alone controller and can be saved in WinCon Projects together with its corresponding user-configured scopes and control panels. WinCon software actually consists of two distinct parts: WinCon Client and WinCon Server.

WinCon Client runs in hard real-time while WinCon Server is a separate graphical interface, running in user mode and it used for displaying the level of water L_1 in tank 1 and L_2 in tank 2 (time diagram).

Quanser power interface makes the connexions between the two tank laboratory equipment and WinCon software, via the data acquisition card installed on the PC.

This interface ensures the compatibility between the digital signals used in WinCon programs and the analogue data of pressure sensors and to control voltage of the pump situated on the two tank equipment.

3.3 Plant control system

The structure of the control system is presented in figure 4. It assures control of the water level inside tank 1 and in tank 2 via the pump voltage [6].

The variables imposed for the control system are:

- the variables in stationary regime are: the operating level, L_{10} L_{20} in tank 1 and tank 2 should be as follows:

$$L_{10} = 15 \text{ [cm]}; \; L_{20} = 15 \text{ [cm]} \tag{1}$$

- the percent overshoot should be less than 1%, i.e.:

$$PO_1 \le 11.0 \; [''\%''], \; PO_2 \le 10.0 \; [''\%''] \tag{2}$$

- the period of the transitory regime: the 2% settling time should be less than 5 seconds, i.e.

$$t_{s\_1} \le 5.0 \text{ [s]}, \; t_{s\_2} \le 20.0 \text{ [s]} \tag{3}$$

- the response should have no steady-state error.

3.3.1 Mathematical model of the plant

Level controller in tank 1 and tank 2 [3]:

$$A_{t1}\frac{dL_1}{dt} = F_{i1}(U_p) - F_{o1}(L_1, A_{o1}) = \\ = k_p U_p - A_{o1}\sqrt{2g}\sqrt{L_1} \tag{4}$$

$$A_{t2}\frac{dL_2}{dt} = F_{o1}(L_1, A_{o1}) - F_{o2}(L_2, A_{o2}) = \\ = A_{o1}\sqrt{2g}\sqrt{L_1} - A_{o2}\sqrt{2g}\sqrt{L_2} \tag{5}$$

where: A_{t1} and A_{t2} are the transversal sections of the tanks, F_{i1}, F_{i2} are the volumetric inflow rates of tank 1 and tank 2: $F_{i1}=k_pU_p$, $F_{i2}=F_{o1}$; F_{o1}, F_{o2} the outflow rates from tank 1 and respectively, from tank 2:

$$F_{o1} = A_{o1}\sqrt{2g}\sqrt{L_1}\,; F_{o2} = A_{o2}\sqrt{2g}\sqrt{L_2} \tag{6}$$

The outlet cross-section area of tank 1 and tank 2 can be calculated by the following equations:

$$A_{o1}=1/4\,\pi\,D^2_{o1} \tag{7}$$

$$A_{o2}=1/4\,\pi\,D^2_{o2} \tag{8}$$

where D_{o1}, D_{o2} are the outlet diameters in tank 1 and tank 2. The nominal pump voltage U_{po} for the pump-tank 1 pair can be determined at the system's static equilibrium.

By definition, the static equilibrium at a nominal operating point (U_{PO}, L_{1O}) is characterized by the water in tank 1 being at a constant position level L_{1O} due to the constant inflow rate generated by U_{PO}.

We can write the static equilibrium voltage U_{PO} as a function of the system's desired equilibrium level L_{1O} and the pump flow constant k_p.

Using the system's specifications and the desired design requirements, we may evaluate U_{PO}. At equilibrium, all time derivative terms are equal to zero: F_{i1}-F_{o1}.

The voltage at equilibrium Upo as expressed below:

$$U_{p0} = \frac{A_{o1}\sqrt{2g}\sqrt{L_{10}}}{K_p} = 9.26 \text{ [V]} \tag{9}$$

$$k_{p0}U_{p0} - A_{01}\sqrt{2g}\sqrt{L_{10}} = 0 \Rightarrow \\ \Rightarrow \sqrt{2gL_{10}} = \frac{k_pU_{p0}}{A_{o1}} \Rightarrow L_{10} = \frac{k_p{}^2U_{p0}{}^2}{2gA_{o1}{}^2} \tag{10}$$

$$A_{o1}\sqrt{2gL_{10}} - A_{o2}\sqrt{2gL_{20}} = 0 \Rightarrow \\ \Rightarrow \sqrt{2gL_{20}} = \frac{A_{o1}\sqrt{2gL_{10}}}{A_{o2}} \Rightarrow \frac{L_{20}}{L_{10}} = \frac{A_{o1}{}^2}{A_{o2}{}^2} \tag{11}$$

But, by linearization of the equation in stationary regime L_{10}, L_{20}, U_{p0} it will provide:

$$A_{t1}\frac{dL_1(t)}{dt} = k_p \Delta U_p - \frac{\sqrt{2g}A_{o1}}{2\sqrt{L_{10}}}\Delta L_1 = \tag{12}$$
$$= \sqrt{2gL_{10}}\Delta A_{o1}$$

$$A_{t2}\frac{dL_2(t)}{dt} = \frac{\sqrt{2g}A_{o1}}{2\sqrt{L_{10}}}\Delta L_1 - \frac{\sqrt{2g}A_{o2}}{2\sqrt{L_{20}}}\Delta L_2 - \tag{13}$$
$$- \sqrt{2gL_{20}}\Delta A_{o2}$$

The time constants and the transfer coefficients have the forms:

$$T_1 = \frac{2A_{t1}\sqrt{L_{10}}}{\sqrt{2g}A_{o1}} \tag{14}$$

$$T_2 = \frac{2A_{t2}\sqrt{L_{20}}}{\sqrt{2g}A_{o2}} \tag{15}$$

$$a = \frac{\sqrt{2g}A_{o1}}{2\sqrt{L_{10}}} \tag{16}$$

$$b = \frac{\sqrt{2g}A_{o2}}{2\sqrt{L_{20}}} \tag{17}$$

$$(T_1 s+1)\Delta L_1(s) = \frac{K_p}{a}\Delta U_P(s) - \frac{\sqrt{2gL_{10}}}{a}\Delta A_{o1}(s) \tag{18}$$

$$(T_2 s+1)\Delta L_2(s) = \frac{a}{b}\Delta L_1(s) + \frac{\sqrt{2gL_{10}}}{b}\Delta A_{o1}(s) - \tag{19}$$
$$- \frac{\sqrt{2gL_{20}}}{b}\Delta A_{o2}(s)$$

3.3.2 Design of the controller parameters

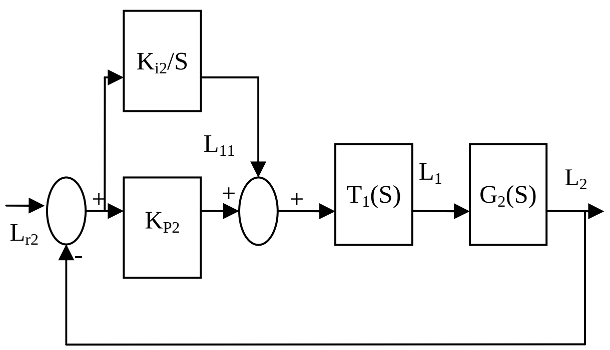

Fig.7 Tank 2 Water level PI control loop

The water level PI control loop is depicted in the diagram 7.

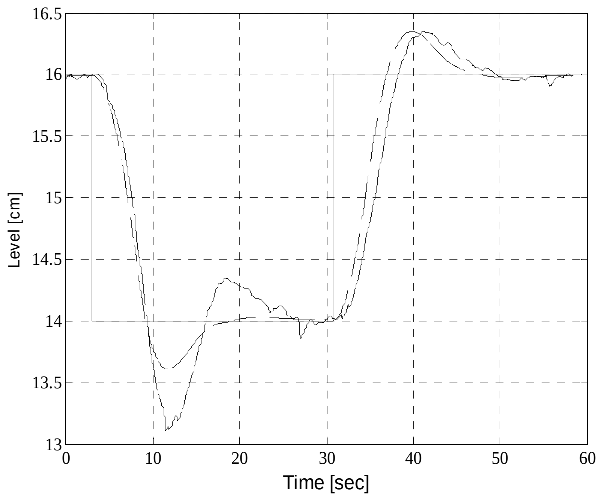

Fig.8 Step response system of L_2 level control

We impose the normalized characteristic polynomial for the closed loop control system of the tank 1 to be [2]:

$$s^2 + \frac{(1+K_{d1}K_{p1})s}{\tau_1} + \frac{K_{d1}K_{i1}}{\tau_1} = 0 \tag{20}$$

The PI controller gains can be expressed as follows:

$$K_{p1} = \frac{2\zeta_1\omega_{n1}\tau_1 - 1}{K_{d1}} \tag{21}$$

and
$$K_{i1} = \frac{\omega_{n1}^2\tau_1}{K_{d1}} \tag{22}$$

The system natural frequency, ω_{n1}, can be calculated as follows:

$$\omega_{n1} = \frac{4}{\zeta_1 t_s} \tag{23}$$

Using the pole placement method, based on imposed control system parameters (1), (2) and (3), it result the following values for controller parameters:

1. K_{p1}=3,6 V/cm
2. K_{i1}=4,55V/s/cm
3. K_{ff1}=2,39V/cm^0.5
4. K_{p2}=5,093 V/cm
5. K_{i2}=1,74 1/s
6. K_{ff1}=1 cm/cm (for two tanks).

The step response of the level control system is presented in figure 8.

3.3.3 Controller design using pole placement

The block diagrams of the closed loop control system are presented in figures 9 and 10 for tanks 1 and 2. Controller design will be realised using the pole placement method. We impose for closed loop control system the following characteristic equation:

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \quad (24)$$

where ζ and ω_n realise the overshoot $\tau \le 11\%$ and the period of the transitory regime $t_r \le 5$ [sec].

By definition, at the static equilibrium point (L_{10}, U_{p0}) [2]:

$$L_1 = L_{10} \text{ and } U_p = U_{p0} \quad (25)$$

Using (7) the voltage feed word gain results to be:

$$k_1 = \frac{A_{01\sqrt{2g}}}{k_p} \quad (26)$$

Evaluation equation (7) with the system's parameters leads to k_1=2.39 [V/$\sqrt{cm}$].

Omissing the feed forward action and carrying out block diagram reduction, tank 1 normalized characteristic polynomial result to be:

$$s^2 + \frac{(1+k_1k_p)s}{\tau_1} + \frac{(1+k_1k_i)s}{\tau_1} = 0 \quad (27)$$

From (27) and (24) the PI controller parameters can be expressed as follows:

$$k_p = \frac{2\zeta\omega_n\tau_1 - 1}{k_1} \quad (28)$$

$$\text{and} \quad k_i = \frac{\omega^2{}_n\tau_1}{k_1} \quad (29)$$

The minimum damping ratio to meet the maximum overshoot requirement PO_1 can be obtained by solving equation:

$$G_1(s) = \frac{k_1}{\tau_1 s + 1} \quad (30)$$

$$\text{where:} \quad k_1 = \frac{k_p\sqrt{gL_{10}}\sqrt{2}}{A_{o1}g} \quad (31)$$

$$\text{and} \quad \tau_1 = \frac{\sqrt{gL_{10}}A_{t1}\sqrt{2}}{A_{o1}g} \quad (32)$$

The following relationship results:

$$\zeta_1 = \frac{\left|\ln\left(\frac{1}{100}PO_1\right)\right|}{\sqrt{\ln\left(\frac{1}{100}PO_1\right)^2 + \pi^2}} \quad (33)$$

The system natural frequency, ω_{n1} as follows:

$$\omega_{n1} = \frac{4}{\zeta_1 t_s} \quad (34)$$

The PI controllers are parameters:

$$k_p = 7.2\left[\frac{V}{cm}\right] \quad (35)$$

$$\text{and} \quad k_i = 9.1\left[\frac{V}{scm}\right] \quad (36)$$

For zero steady-state error, tank 1 water level is controlled by means of a Proportional-Integral (PI) closed-loop scheme with the addition of a feedforward action, as illustrated in figure 9.

As depicted in figure 9, the voltage feedforward action is characterized by:

$$V_{p\_ff} = K_{ff\_1}\sqrt{L_{r\_1}} \quad (37)$$

$$\text{and} \quad V_p = V_{p1} + V_{p\_ff} \quad (38)$$

As it can be seen in figure 9, the feedforward action is necessary since the PI control system is designed to compensate for small variations (disturbances) from the linearized operating point (L_{10}, V_{p0}) [6].

In other words, while the feedforward action compensates for the water withdrawal (due to gravity) through tank 1 bottom outlet orifice, the PI controller compensates for dynamic disturbances.

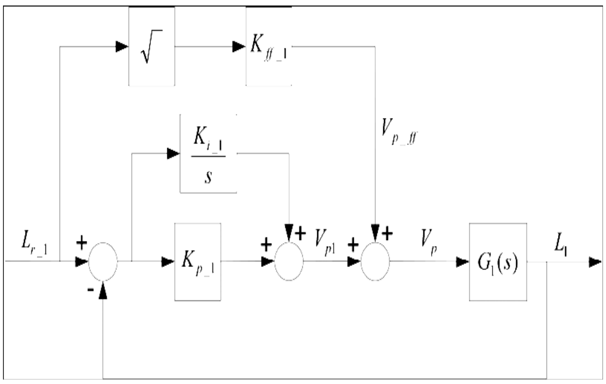

Fig.9 Tank 1 water level PI feedforward control loop

The open-loop transfer function $G_1(s)$ takes into account the dynamics of the tank 1 water level loop, as characterized by the equation 39:

$$G_1(s) = \frac{L_{11}(s)}{V_{p1}(s)} \tag{39}$$

However due to the presence of the feedforward loop, $G_1(s)$ can also be written as follows:

$$G_1(s) = \frac{L_1(s)}{V_p(s)} \tag{40}$$

For zero steady-state error, tank 2 water level is controlled by means of a Proportional - Integral (PI) closed-loop scheme with the addition of a feedforward action, as illustrated in figure 10.
In the block diagram depicted in figure 10, the water level in tank 1 is controlled by means of the closed-loop system previously designed. This is represented by the tank 1 closed-loop transfer function defined below:

$$T_1(s) = \frac{L_1(s)}{L_{r\_1}(s)} \tag{41}$$

Such a subsystem represents an inner (or nested) level loop. In order to achieve a good overall stability with such a configuration, the inner level loop (i.e. tank 1 closed-loop system) must be much faster than the outer level loop. This constraint is met by the previously stated controller design specifications, where $t_{s\_1} << t_{s\_2}$ [5].
However for the sake of simplicity in the present analysis, the water level dynamics in tank 1 are neglected. Therefore, it is assumed hereafter that:

$$L_1(t) = L_{r\_1}(t) \tag{42}$$

and $T_1(s) = 1$ (43)

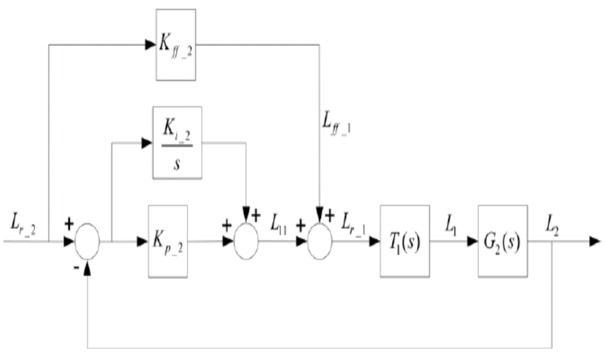

Fig.10 Tank 2 water level PI feedforward control loop

Furthermore as depicted in figure 10, the level feedforward action is characterized by:

$$L_{ff\_1} = K_{ff\_2} L_{r\_2} \tag{44}$$

$$L_{r\_1} = L_{11} + L_{ff\_1} \tag{45}$$

The level feedforward action, as seen in figure 10, is necessary since the PI control system is only designed to compensate for small variations (disturbances) from the linearized operating point (L_{20}, L_{10}). In other words, while the feedforward action compensates for the water withdrawal (due to gravity) through tank 2's bottom outlet orifice, the PI controller compensates for dynamic disturbances.
The open-loop transfer function $G_2(s)$ takes into account the dynamics of the tank 2 water level loop, as characterized by the next equation [4, 6]:

$$G_2(s) = \frac{L_{21}(s)}{L_{11}(s)} \tag{46}$$

However due to the presence of the feedforward loop $G_2(s)$ can also be written as follows:

$$G_2(s) = \frac{L_2(s)}{L_1(s)} \tag{47}$$

4 Experimental results

4.1 Mathematical models using additive faults and disturbances for the didactical plant

The faults we are dealing with may arise in the basic technological equipment or in its measurement and control instruments (sensors and actuators). They may represent performance deteriorations (such as the actuator transfer coefficient or bias in a sensor), partial malfunctions (such as leaks from a tank or a pipeline) or total breakdowns (such as the loss of a pump or a sensor) [1].

From the point of view of diagnosis, it's of interest how a particular fault affects the outputs plant. We consider in plant mathematical model (18) and (19) the additive faults.

In this case the mathematical model has the form:

$$(T_1 s + 1)\Delta L_1(s) = \frac{K_p}{a}\Delta U_P(s) - \frac{K_d}{a}\Delta U_P(s) - \\ - \frac{\sqrt{2gL_{10}}}{a}\Delta A_{o1}(s) - \Delta F_l \tag{48}$$

$$(T_2 s+1)\Delta L_2(s)=\frac{a}{b}\Delta L_1(s)+\frac{\sqrt{2gL_{10}}}{b}\Delta A_{o1}(s)-\frac{\sqrt{2gL_{20}}}{b}\Delta A_{o2}(s) \quad (49)$$

where K_d the fault actuator transfer coefficient and ΔFl is the flow corresponding to possible leaks in the tank 1 or in the pipe between tanks 1 to tank 2.

The PI controller may have bias sensor faults. In this case the PI algorithm has the following form:

$$\Delta U_p(s)=\frac{T_i s+1}{T_i s}K_R\Delta L_1 \quad (50)$$

$$\Delta U_p(s)=-\left(1+\frac{K_{i1}}{s}\right)\Delta L_1(s)+\left(1+\frac{K_{i1}}{s}\right)\Delta L_d(s) \quad (51)$$

where ΔL_d is the sensor fault.
These faults, which can occur in the actuator (pump K_d), sensors (ΔL_d) or leak (ΔF_l) will be presents in the transitory or steady state response of the system. We can detect the present faults analysing the system response.

4.2 The experimental faults detection

In the plant, the next additive faults may appear: sensor faults, actuator faults, faults plant (leaks), disturbances plant, sensor noises, actuator noises, and noises plant.

Major faults: the growth of the drain section ΔS_1 is equivalent with a broken pipe at the water transfer from Tank 1 to Tank 2 (figure 11).
- t=0÷17 seconds - the plant starts with a major fault. We can highlight the measure noise and the error of the real value of the level up set point and the output of the model;

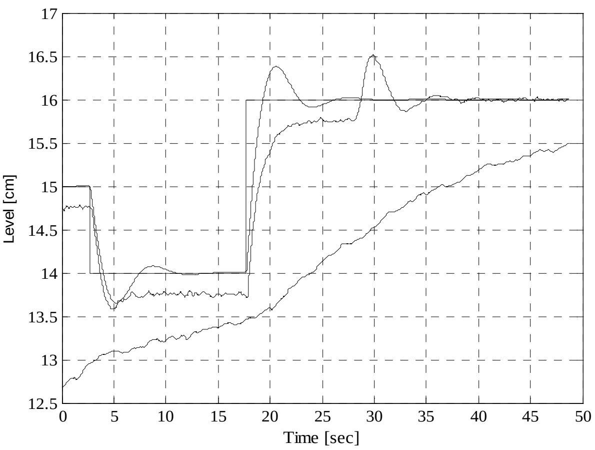

Fig.11 The response of the system at major faults

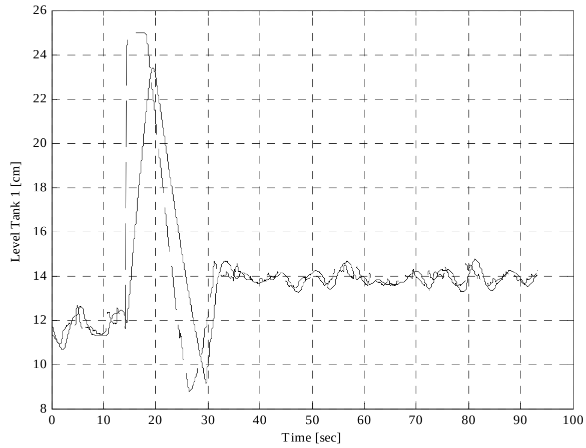

Fig.12 Response of L_1 in tank 2

- t=17÷27 seconds - the response of the system at a step variation of the set point with a major fault;
- t=27 seconds - the fault was eliminated and we can notice that the measured variable overlaps the output variable from the model of simulator, and only the measured noise is present, that will lead to small variations of the measured variable value from its real value.

By this way, based on the response of the system at different input signals, we can observe the major faults which appear in the technological part of the control system (see figure 12).

Pump noises in combination with minor faults in the plant:
- The noise at the pump (u_p): in the installation from drain regime at flow of the pump in Tank 1, at drain flow on Tank 1 in Tank 2 disturbances similar to air bulls appear, which modifies the fluid density, therefore modify the hydrostatic pressure:

$$\rho_H=\rho gL \quad (52)$$

the measurement sensors for the determination of the level of the fluid in the tanks.
The water level in Tank 2 is controlled by controlling the outflow through Tank 1.
PI controllers command the pump flow that influences the level in tank 1.
In figure 11 the response of the level L_2 is presented, at step set point for the tank 2.
- The noise at the pump (u_c): the noise given by the drain flow through the pipe and the noise of the rotary pump appear.
In the absorbability process and pump, at water pressure variations appear and because of the nonlinear characteristic of the pump, the flow F_i is not proportional with V_p, but will be accompanied by the command noise:

$$F_i=KV_p+\Delta F_i \quad (53)$$

In figure 13 is presented the perturbation response of the level L_2, at the controller pump command.

- The noise of the sensors (y): the small sensibility at the sensors (15 mV/1 bar) will introduce a measure noise, which appears in the electronic amplifier which transforms the output voltage of the grow sensors into an analogue signal of 10 V. Beginning from the 48th second, the diagram presented in figure 13 shows the step response of the level control system under perturbation conditions.

In figures 14 and 15 we can put observe the real and simulation responses of the plant.

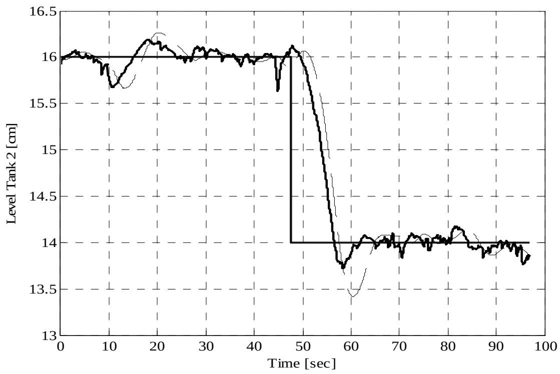

Fig.13 Perturbation response of L_2 level

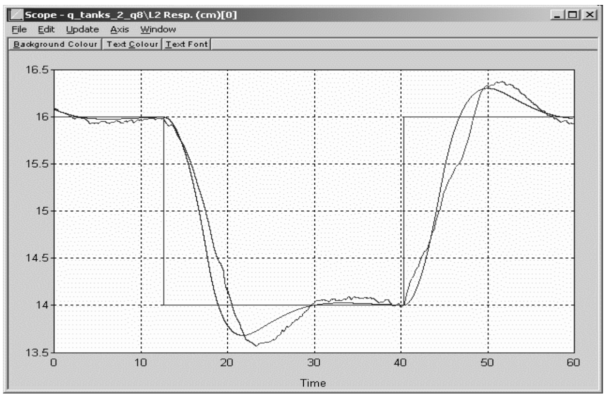

Fig.14 Real response of the L_2

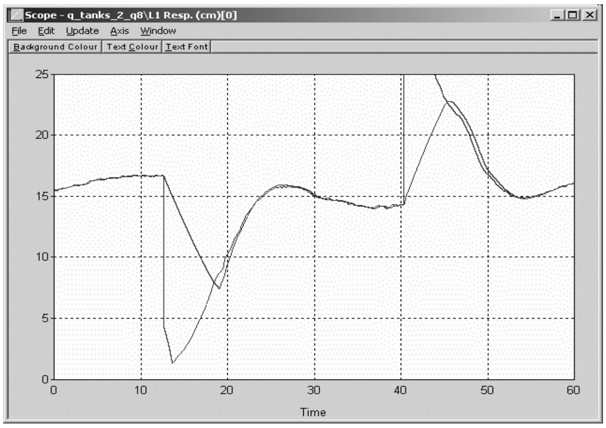

Fig.15 Real response of the L_1

5 Conclusions

This paper presents a methodology for using the results of a simulation on a laboratory installation in the level control in coupled tanks.

In the plant, we can put observe the next additive faults: sensor faults, actuator faults, faults plant (leaks), disturbances plant, sensor noises, actuator noises, and noises plant, major faults: the growth of the drain section ΔS_1 is equivalent with a broken pipe at the water transfer from Tank 1 to Tank 2, pump noises in combination with minor faults in the plant: the noise at the pump (u_p), the noise at the pump (u_c), the noise of the sensors (y).

The research will be extended to also implement modelling algorithms and detection and localisation of the possible faults types that appear in the plant.

This paper has been financially supported by the CNCSIS grant type TD and is part of the research activities in the Automation Department, Faculty of Automation, Computers and Electronics, University of Craiova.

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