

TCFW
Temperature Control
of Flowing Water

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Liberec 2013

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CONTENT

1	Aims of the experiment	2
2	Description of the process.....	3
2.1	Construction	3
2.2	Function	3
2.3	I/O card	5
3	Process analysis.....	6
3.1	Determination of the structure of the loop to be modeled	6
3.2	Determination of steady state behavior	7
3.3	Experimental identification	7
3.3.1	<i>Identification measurement.....</i>	<i>8</i>
3.3.2	<i>Transfer function parameters estimation – data analysis.....</i>	<i>9</i>
4	Determination of controller setting	11
4.1	Experimental controller setting	11
4.2	Controller setting for the optimum magnitude.....	12
5	Study of the real control process	14
6	Literature	15

1 AIMS OF THE EXPERIMENT

There are several aims of the experiment (Fig. 1).

- 1) Analysis of the prescribed controlled system.
 - a. Process analysis, design and implementation of identification measurements.
 - b. Determinations of the transfer function of the controlled system on the basis of the experimental identification.
- 2) Creating of a closed loop model using some software tool (Matlab/LabView).
- 3) Determination of the controller setting values on the model
 - a. by experimental testing (manual tuning),
 - b. according to the defined optimum.
- 4) Investigation of the closed loop with the controller setting values detected
 - a. on the model,
 - b. on the real device.



Fig. 1: Picture of the process

2 DESCRIPTION OF THE PROCESS

2.1 CONSTRUCTION

The structure of the laboratory test rig is shown in the Fig. 2. A functional diagram with the measurement loop and signal representation is shown in Fig. 3.

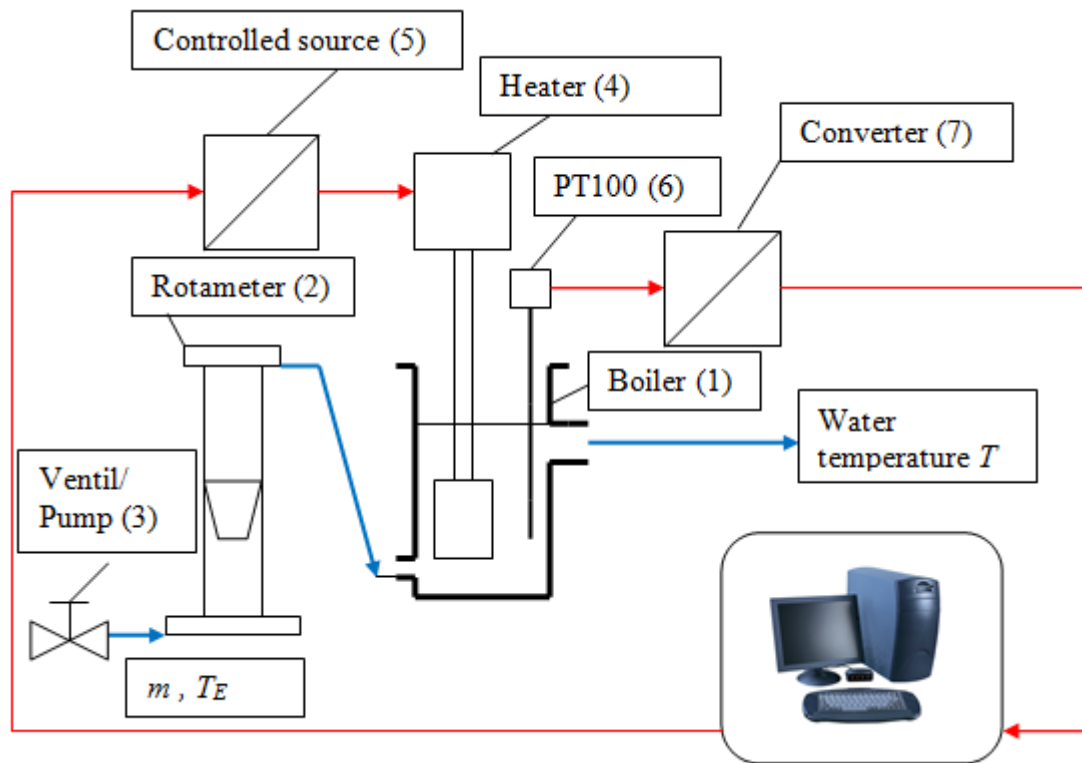


Fig. 2: Structure of the experimental setup

2.2 FUNCTION

The description is made with reference to the Fig. 2 and Fig. 3.

- 1) Water flows through a water container/boiler (1) with an open water surface. The mass flow in kg/s is measured by a rotameter (2) (variable-area flow meter) and controlled by a pump (3). The water temperature $T_E(t)$ at the entrance of the container is not measured, but the temperature $T(t)$ at the output is measured.
- 2) An electric heater (4) is used for water heating. The electrical output of the heater is adjusted by an electric power control unit (5). This device has the external control voltage u_0 in the range of 0 – 10 V. At the output of the device, the electrical power P is varied in the range of 0 – 680 W.
- 3) The water temperature in the water tank (the resistance thermometer PT100 (6) is used) is converted by a converter (7) into a voltage u_T .

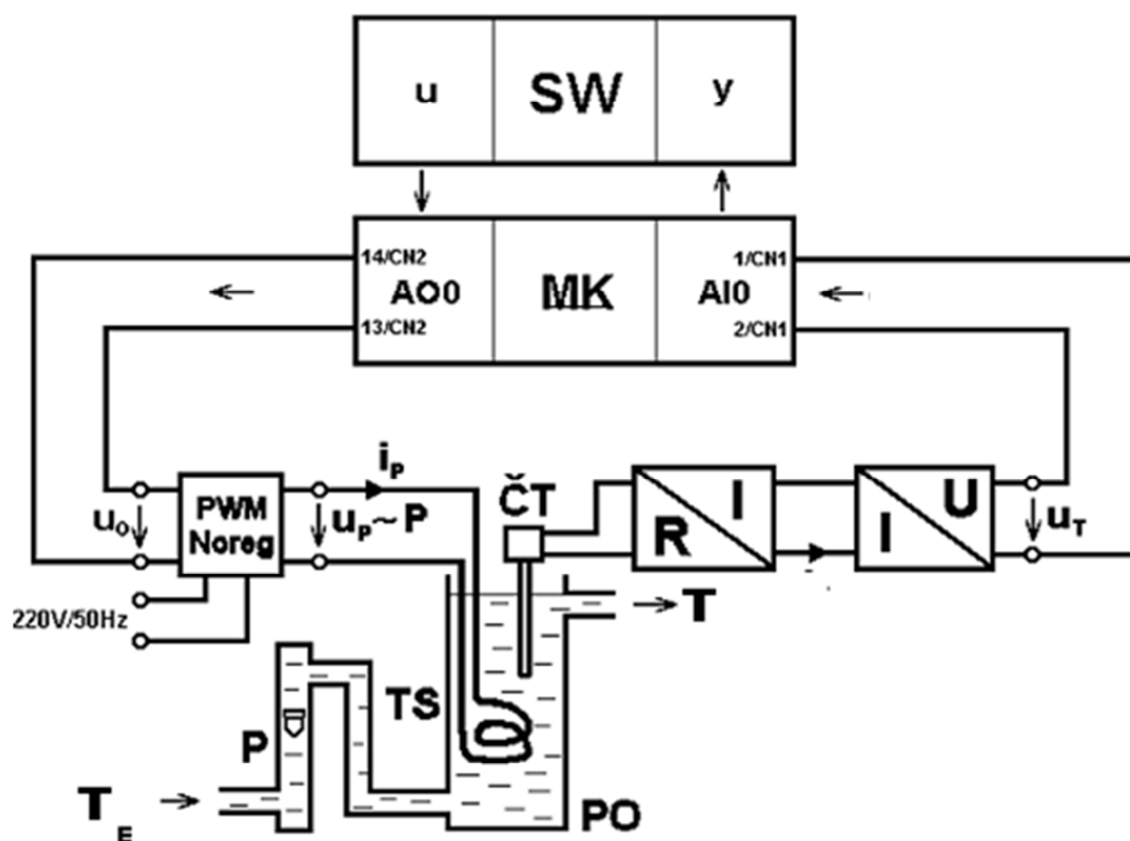


Fig. 3: Functional diagram

Tab. 1: Device description

Symbol	Description
PO	Boiler container
P	Flowmeter (rotameter)
TS	Heater
PWM	Power control device
ČT	Temperature sensor PT100
SW	Software on the PC
R/I	Resistor/current converter
I/U	Current/voltage converter
MK	I/O data acquisition card in the PC, Advantech PCI 1711
AO0	Analog output of the I/O data acquisition card
AI0	Analog input of the I/O data acquisition card

Tab. 2: Description of signals and variables

Signal	Description	Value
u	Manipulating variable in the PC (I/O card SW value)	0 ..10 (V)
u_0	Control voltage from the PC	0 ..10 V
u_T	Output voltage of the converter	0 ..10 V
u_P	Heater voltage	0 ..230 VAC
y	Process output variable in the PC (I/O card SW value)	0 ..10 (V)
T_E	Water temperature at the inlet of the heater	0 ..100 °C
T	Water outlet temperature from the heater	0 ..100 °C
P	Heating power	0 ..680 W

To carry out the measurements using a PC, the I/O data acquisition card is used. For the measurements, and real-time control of the systems, the special software is used. The using of LabView and/or Matlab is preferred in this application. A block diagram of the experiment with the signals is shown in the Fig. 3.

2.3 I/O CARD

For this experiment the programming of the I/O card is not described in detail. The card will only be described as far as is necessary to fulfill the task. The input and output channels (ports) of the I/O card are controlled digitally. The input channel, which is intended for measuring the temperature sensor output signal, passes a decimal number in the range 0 V to 10 V to the computer. The output channel for generating the control voltage of the electrical heating power is controlled from computer by a decimal number in the range 0 V to 10 V.

3 PROCESS ANALYSIS

A mathematical model can be found on the basis of physical laws. Another way is the experimental identification. In the laboratory experiment, the experimental identification is used and preferred for modeling.

3.1 DETERMINATION OF THE STRUCTURE OF THE LOOP TO BE MODELED

Before starting the measurement you have to decide which part of the system or the loop has to be modeled. That determines which signals have to be measured. A control loop consists in accordance with DIN 19 221 of the following five major components (Fig. 4):

- control system,
- control element,
- measuring equipment,
- calculating of the controlling and task variable.

The signals in the loop are in line with the international designation and vary slightly from the DIN Standard 19 221 [12].

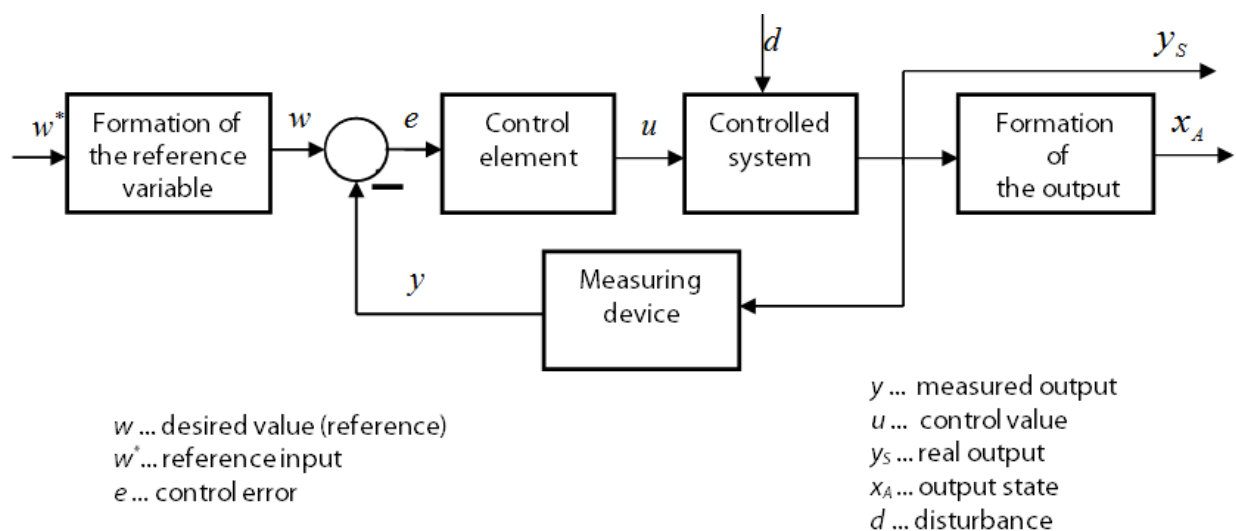


Fig. 4: Closed loop

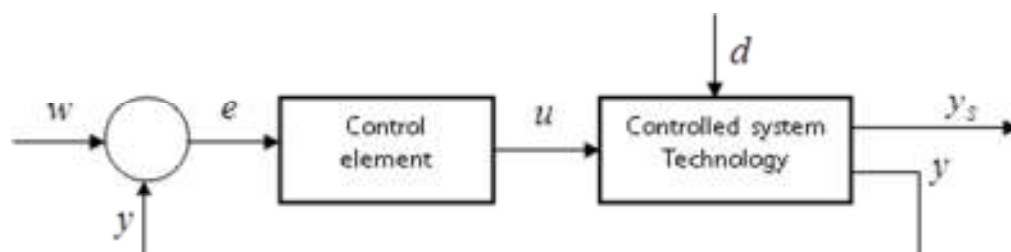


Fig. 5: Simplified block diagram of a control loop

The simplified block diagram of a control loop, which is realized with only two blocks, is shown in Fig. 5. Here, the controlled system, measuring device, transducer, actuator, etc., are combined [2] in the block 'Controlled system – Technology' which is often marked as 'Advanced control system'.

Task 1: Preparation

- a) Create from the functional diagram a detailed technical control block diagram and determine the following parts:
 - i) Advanced control system (a simplified block diagram of the plant).
 - ii) Closed loop according to DIN 19 221.
- b) Determine the range of the manipulating variable $u(t)$, the ranges of $y(t)$ and $T(t)$. Indicate the physical units.
- c) Determine the input to the measuring device.
- d) Explain which variables influence the process output variable – the temperature $T(t)$. Can this change be described as an effect of some disturbance $d(t)$?



3.2 DETERMINATION OF STEADY STATE BEHAVIOR

The determination of the steady state behavior requires from the extended controlled system that at the entrance to the process a constant input signal is applied and the output signal has reached the steady state.

Task 2: Determination of the steady state behavior of the process

Construct the steady state characteristic. The measurement of the steady state behavior for the whole range of the manipulating variable is very time-consuming. For this reason, a file with this measurement is prepared.

- a) Use the LabView program to read and process the control values and measured output values from the specified file.
- b) The static characteristic, the steady state behavior $y(\infty) = f(u(\infty))$ graph, is constructed automatically by the program from data points inside the table. **Fill the table with data points which you find on graph in steady states.**
- c) The graph with measurement (process and manipulating variables) and the static characteristics have to be printed and described.
- d) Find the transfer characteristic between the real temperature in Celsius and the measured value. If you know, that

$$T = 17.14u_T - 44.85 \quad (1)$$

- e) Determine the linear range of the process.
- f) **Choose a position of your working point.**



3.3 EXPERIMENTAL IDENTIFICATION

Following the structure of the control circuit, according to DIN 19 221, two structures and correspondingly two mathematical models are defined [10]:

- a) A linear model of the advanced controlled system (process) is defined by a transfer function $F(s) = Y(s) / U(s)$ (see Fig. 6a).
- b) A linear model of the effect of flow (see Fig. 6b) is determined through two transfer functions $P(s), H(s)$.

The transfer function $P(s)$ approximates the dynamic characteristics of the physical process (without measuring device) and the transfer function $H(s)$ approximates the dynamic properties of the measuring device.

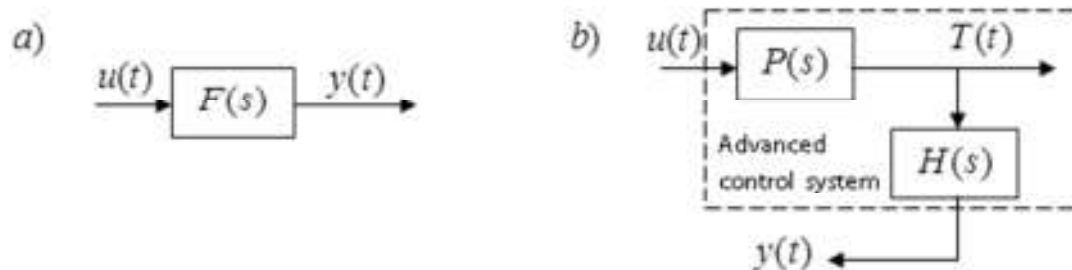


Fig. 6: Model structure of the advanced controlled system (a), model structure of the action sequence (b)

It is assumed that the mean of the noise on the measured output signal is equal to zero. The experimental identification can be divided into three steps:

- Design and implementation of identification measurements.
- Evaluation of the measurements.
- Verification of the calculated mathematical model.

3.3.1 Identification measurement

Provide that the identification measurement begins in steady state of the track. The step change of the control value in each measurement cycle can be performed only after reaching the steady state. The mass flow F should be constant and equal to 13 l/h (try manually holding this value by changing the pump power). The identification measurement uses the LabView program. With the help of this program is the changing of the control value generated and the course of the manipulating variable and process output variable saved and online watchable.

The step change of the manipulating variable is determined using the slider. The time course of the manipulating variable $u(t)$, the process output variable $y(t)$ and the time t is saved into a data file and a variable. The file name has to be changed according the group identifier.

The first step has to be a step into the working point, and then you should realize two steps up and finally one step down to the working point. The response of first two steps is used to identify the route. The response to the last step can be used to identify the process dynamic behavior in a case of a cooling (descending the heater power).

Task 3: Investigation of the real process, advanced control system

Made the identification measurement in the LabView with these default parameters:

- **sampling period** $T = 1 \text{ s}$
 - **measurement cycle time** $T_Z = 300 \text{ s}$
 - **number of cycles** $n_Z = 4 (3)$
- Design the course of the manipulating variable according to the described rules. Use the change of the manipulating variable in a range $\Delta u = +0.5 \text{ V}$ to $\Delta u = +1.5 \text{ V}$ from the operating point in the case of increasing the heater power. Every new step on the manipulating variable should be done after the measurement cycle time T_Z (system reach the steady state).

- b) Select the file name and start the identification measurement.
- c) **The mass flow rate has to be approximately 13 l/h. Adjust if necessary by changing the pump source voltage!**
- d) Watch the course of manipulating variable $u(t)$ and process output variable $y(t)$.
- e) Print the step response of the advanced control system and the manipulating variable together.



3.3.2 Transfer function parameters estimation – data analysis

The LabView program is used to determine the parameters of the transfer function $F(s)$. The experiences and some knowledge from physical process analysis lead to the prediction the transfer function of this process has three time constant and any zeros. The typical behavior of such a systems; heating processes; is a very slow charging when the output seems to be in a steady state. The impact is different gain of the process when you increase and decrease the manipulating variable. Therefore you should finally find two transfer functions from the measurement. The first transfer function $F_H(s)$ approximates the heating (increasing the manipulating variable), the second $F_C(s)$ the cooling (decreasing of the manipulating variable). The program calculates the parameters of both transfer functions from the second, third and fourth jump. The general form of both transfer functions has the following predefined structure

$$F(s) = \frac{B(s)}{A(s)} = \frac{K}{(T_1s + 1)(T_2s + 1)(T_3s + 1)} \quad (2)$$

where T_1, T_2, T_3 are time constants and K is the gain.

Because the initial conditions of the transfer function must be according to the zero, in the first step the working point is found. For this operating point, the measurement data are converted using the following formula

$$\begin{aligned} \Delta y(k) &= y(k) - y_0, \\ \Delta u(k) &= u(k) - u_0. \end{aligned} \quad (3)$$

where

- $y(k)$ is the measured process output variable,
- $u(k)$ is the measured manipulating variable,
- y_0, u_0 is position of working point.

First, the operating point u_0 and y_0 is determined for the steady state in the first measurement period from the average value of $y(k)$ and the first manipulating variable value $u(1)$. The working point is marked in the graphical representation. In the second step, the parameters of the polynomials $A(s), B(s)$ are searched. The gain factor K can be also calculated directly from the steady state! The last step is the estimation of the part, where the cooling is provided.

The output signals with the same input signals of the measurement and the model are compared with each other. The resulting deviation between measured and calculated dynamic course is the minimization of the quadratic functional form $J(x)$

$$J(x) = \sum_k (y(k) - y_m(k))^2 = \sum_k (y^P(k) - y_i(k))^2 = \sum_k (\Delta y(k))^2 \rightarrow \min \quad (4)$$

The general scheme of this identification process is shown in Fig. 7. The parameter search process is implemented using the LabView minimize function. Another way is to use directly the block of parameter estimation.

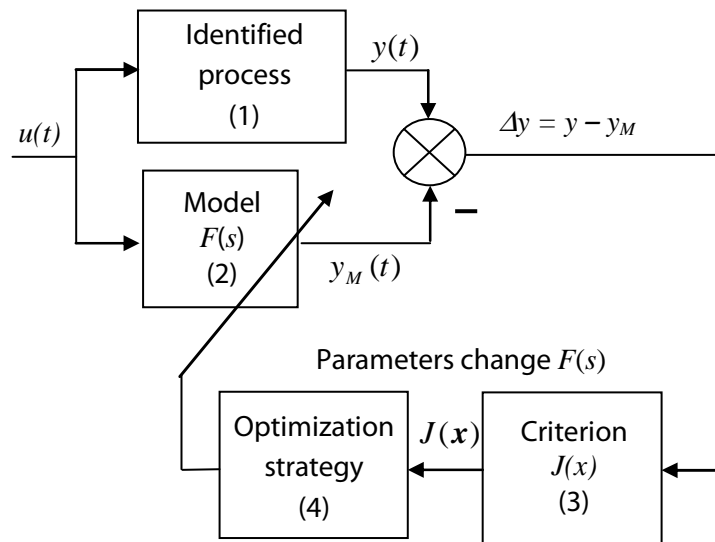


Fig. 7: The identification structure

Task 4: Transfer functions $F_H(s)$ and $F_C(s)$ parameters estimation

Use prepared LabView program to find parameters of transfer functions for heating and transfer function of cooling. Firstly try to find optimal parameters manually (by some intelligent changes on all unknown parameters, secondly use automatic algorithm to search the optimum.

- Run the parameter estimation program. The input file with your measurement has to be specified before you start.
- Use first tab to manual searching of heating transfer function parameters.
- Use second tab to the automatic parameters estimation.

The following tests are made with changes on the manipulating variable Δu from the task 3. The following must be printed and included:

- Representation of the function curves $y(kT)$ and $u(kT)$ to check whether the correct file is being processed.
- Display of the working point in the function curves $y(kT)$ and $u(kT)$.
- The course of variables $\Delta u(kT) = u(kT) - u_0$, $\Delta y(kT) = y(kT) - y_0$, which enter to the parameters estimation process.
- The response of the optimal transfer functions to your manipulating variable together with measured process output variable.

Discuss the results. Focus to differences between transfer functions for heating and cooling. Describe the process of manual parameters estimation process and comment your results/success.

4 DETERMINATION OF CONTROLLER SETTING

The controller setting can be determined either experimentally or by calculation. In this experiment, the PI controller parameters have to be determined by experimental testing and by direct calculating of the controller parameters using the method to determine the optimum magnitude.

4.1 EXPERIMENTAL CONTROLLER SETTING

The simplest method for the controller parameter tuning is setting parameters by hand. This process takes place at a controller with the transfer function by the following procedure.

- 1) Models of the closed control loop or a real control loop are available.
- 2) I and D components are set to zero.
- 3) The P component is increased until the required speed is achieved.
- 4) The steady state error is eliminated with the increasing of the I component.

With this simple procedure good result can be achieved by a logical, successive approach.

The computed mathematical model of the plant can be used in a closed control loop for the experimental setting of the controller's parameters. The block diagram in Fig. 8 illustrates the structure of a simulation model which helps in the process of manual controller tuning. The figure shows a simulation diagram of the closed loop and the open loop.

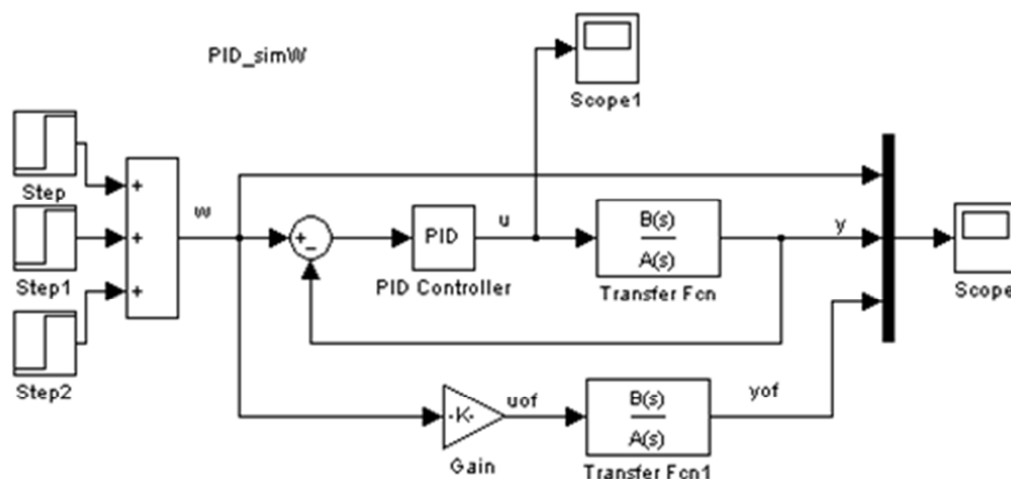


Fig. 8: Simulink model of the closed loop to tune the controller's parameters

The simplest criterion of the quality of the closed loop is to assess the comparison of the output signal y of the closed control loop with the output signal y_{of} of the track whose input is the step signal u_{of} . The signal u_{of} must be so high that the steady state of the y_{of} is equivalent to the set point $w(t)$. This is satisfied through the right setting of the block 'Gain'.

Step responses of the closed control loop and the open loop can be compared with each other to evaluate the effect of the controller. With the gain 'Gain' is the open loop set so that the steady-state values of the control loop and the open loop are the same.

The general structure of the PI controller is

$$R(s) = P + \frac{I}{s}. \quad (5)$$

Task 5: Control the model with PI controller

Construct the model in LabView (by Fig. 8) to be able to tune PI controller's parameters. Find PI controller setting which satisfy all defined conditions:

- **The controller is optimal to track the step reference changes.**
- **The maximal overshoot is less than 5 %.**
- **The settling time bellow 250 s.**

The program main functions are:

- a) Simulation of a closed loop.
- b) Simulation of an open loop with the gain.
- c) Display in one graph reference signal, closed loop response and open loop response. The second graph should display the manipulating variable (controller output) from closed loop.

Notes for the evaluation:

- d) Calculate the gain (block 'Gain') for comparison with the control loop.
- e) Manually find PI controller setting values for reasonable $w(t)$. The optimal choice is a unit step.
- f) Describe the procedure of tuning and the results $y(t), w(t)$.
- g) Check the course of the manipulating variable and focus to their extremes.
- h) Discuss the results.



4.2 CONTROLLER SETTING FOR THE OPTIMUM MAGNITUDE

The optimum magnitude method [1, 8] provides a favorable setting of the control parameters. It does not represent a true optimization, because it does not assumes a quality criterion which is minimized. The process will have the character of a pure delay system. The control processes are relatively slow. Suppose the PI controller in the form

$$R(s) = P + \frac{I}{s} = K_R T_R + \frac{K_R}{s} = K_R \left(\frac{1 + T_R}{s} \right). \quad (6)$$

- a) According to the optimum magnitude for a process with a dominant time constant T_1 (see [1] page 260) it is possible to write

$$F(s) = \frac{K_S}{\prod_{v=1}^n (T_v s + 1)} \approx \frac{K_S}{(T_1 s + 1)(T_\Sigma s + 1)} = F_{APR}(s), \quad (7)$$

$$T_1 \gg T_\Sigma = \sum_{v=2}^n T_v.$$

The PI controller setting is

$$K_R = \frac{1}{2K_S T_\Sigma}, \quad T_R = T_1. \quad (8)$$

- b) According to the optimum magnitude for a transfer function with two dominant time constants T_1, T_2 in the form

$$F(s) = \frac{K_S}{\prod_{v=1}^n (T_v s + 1)} \approx \frac{K_S}{(T_1 s + 1)(T_2 s + 1)(T_\Sigma s + 1)} = F_{APR}(s), \quad (9)$$

$$T_1, T_2 \gg T_\Sigma = \sum_{v=3}^n T_v.$$

are the PI controller parameters equal to

$$K_R = \frac{T_1^2 + T_1 T_2 + T_2^2}{2K_S(T_1 + T_2)T_1 T_2}, \quad T_R = \frac{(T_1^2 + T_2^2)(T_1 + T_2)}{T_1^2 + T_1 T_2 + T_2^2}. \quad (10)$$

If the transfer function is not the special case with one or two dominant time constants, then the full calculation according to [1] is used.

Task 6: Calculation of controller parameters according to the optimum

Calculate the controller parameters according to the optimum for $F_H(s)$.

- Study the control process with optimum parameters on the model.
- Check the response for the unit step on the reference and find the value of overshoot and the settling time. Optionally you can look up for a rise time. Use the same simulation scheme/program as in a previous task to display the response.
- Check that the manipulating variable remains within the specified range.
- If the controller setting for optimum magnitude leads to a 'lazy' and 'careful' control process, try to correct this setting manually.
- Discuss the results.



5 STUDY OF THE REAL CONTROL PROCESS

The real controlled system is using the PC with the multifunctional measurement card Advantech PCI-1711 inside. To verify the behavior of both controllers on the real system use prepared LabView program.

Task 7a: Control of the real plant

Examine the behavior of the closed loop with the real process with the determined controller setting from manual tuning. Use prepared LabView program to test the controller function. The functional profile of the reference value $w(t)$ should be formed by the sequence of jumps.

Notes for the evaluation:

- Compare results from real process control with the studies on the model. Compare both important variables: manipulated variable $u(t)$ and process output variable $y(t)$.
- Discuss results.



Task 7b: Control of the real plant

Examine the behavior of the closed loop with the real process with the determined controller setting from optimal module criterion. Use prepared LabView program to test the controller function. The functional profile of the reference value $w(t)$ should be formed by the sequence of jumps.

Notes for the evaluation:

- Compare results from real process control with the studies on the model. Compare both important variables: manipulated variable $u(t)$ and process output variable $y(t)$.
- Discuss results.



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