Otto-von-Guericke-University Magdeburg
Faculty of Electrical Engineering and Information Technology
Institute for Automation Engineering

Automation Lab

Temperature Control Lab 2 (TCL2)
Report

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1 Preparation

- Gaining experience with standard controllers.
- Application of simple standard methods to design controllers in the frequency domain.

1.1 Task 1

The transfer function obtained by Tangent Method in TCL 1 is used to design the PI controller in the frequency domain:

- Transfer Function $G(s)$ of the system from TCL1 in time and frequency domain respectively.

$$G(s) = \frac{0.635}{(1+23.05s)(1+138.3s)} = \frac{0.635}{(1+23.05jw)(1+138.3jw)}$$

- Controller Transfer function $G_C(s)$ is

$$G_C(s) = K_p + \frac{K_i}{s} = \frac{K_i}{s}(1 + s\frac{K_p}{K_i})$$

- Open loop transfer Function $G_O(s)$, where $\frac{K_p}{K_i}$ =138.3 to make the system Type-1.

$$G_O(s) = G(s).G_C(s) = \frac{0.635K_i}{s(1+23.05s)}$$

1.1.1 Gain adjustment with phase margin Φ_M = 30° and Φ_M = 70°.

Bode-diagram of open-loop transfer function $G_O(s)$ fig1.1.1 for $K_i = 1$; This is performed to get the adjustment gain for phase margin $\Phi_M = 30°$ and $\Phi_M = 70°$

to small

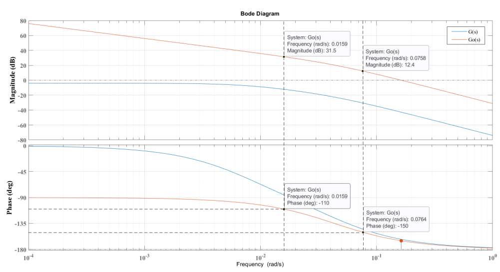

Figure 1.1.1: Bode Plot of G(s) and $G_O(s)$ with K_i=1

- **Phase margin Φ_M = 30°**
  -12.4db gain to be adjusted to get phase margin of $\Phi_M = 30°$. Therefore,$K_i = 10^{\frac{-12.4}{20}}$ $K_i = 0.2398$; $K_p = (138.3).(0.2398) = 33.164$. Adjusted Open loop transfer Function $G_{O30}(s)$ and Controller Transfer function $G_{C30}(s)$ are

$$G_{O30}(s) = \frac{0.1523}{s(1 + 23.05s)} \qquad G_{C30}(s) = 33.164 + \frac{0.2398}{s}$$

- **Phase margin Φ_M = 70°**
  -31.5db gain to be adjusted to get phase margin of $\Phi_M = 70°$. Therefore,$K_i = 10^{\frac{-31.5}{20}}$ $K_i = 0.0266$; $K_p = (138.3).(0.0266) = 3.678$. Adjusted Open loop transfer Function $G_{O70}(s)$ and Controller Transfer function $G_{C70}(s)$ are

$$G_{O70}(s) = \frac{0.01689}{s(1 + 23.05s)} \qquad G_{C70}(s) = 3.678 + \frac{0.0266}{s}$$

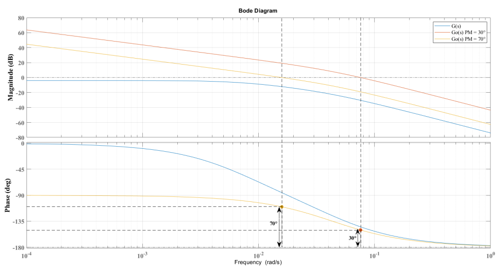

Figure 1.1.2: Bode Plot of $G_{O30}(s)$ and G$_{O70}(s)$

1.1.2 Loop Shaping

Try to improve the results of fig 1.1.2 by increasing the crossover frequency while keeping the phase margin constant.
In order to do the same, a lead compenstor is required

$$G_L(s) = \frac{T_L s + 1}{(\alpha * T_L s) + 1} \qquad T_L = \frac{1}{\omega_m * \sqrt{\alpha}} \qquad \alpha = \frac{1 - sin(\Phi_{Max})}{1 + sin(\Phi_{Max})}$$

- **Phase margin Φ_M = 30°**
  +12.4db gain is multiplied with $G_{C30}(s)$ and lead-compensator $G_{L30}(s)$ with $\omega_m = 0.163 rad/s$ and Φ_{Max}=18° to get phase margin of $\Phi_M = 30°$ with an increased frequency from 0.0757rad/s to 0.198rad/s as shown in fig 1.1.3.

$$G_{L30}(s) = \frac{8.445s + 1}{4.457s + 1} \qquad G_{C30}(s) = 33.164 + \frac{0.2398}{s}$$

$$G_{O30Lead}(s) = 4.1 * G_{C30}(s) * G_{L30}(s) = \frac{5.35s + 0.6336}{102.7s^3 + 27.51s^2 + s}$$

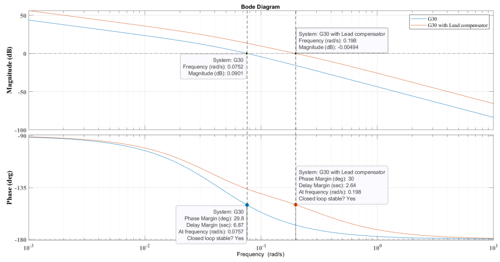

Figure 1.1.3: Bode Plot of $G_{O30Lead}(s)$

- **Phase margin Φ_M = 70°**
  +22.9db gain is multiplied with $G_{C70}(s)$ and lead-compensator $G_{L70}(s)$ with $\omega_m = 0.163rad/s$ and Φ_{Max}=60° to get phase margin of $\Phi_M = 70°$ with an increased frequency from 0.01592rad/s to 0.221rad/s as shown in the fig 1.1.4.

$$G_{L70}(s) = \frac{22.9s+1}{1.644s+1} \qquad G_{C70}(s) = 3.678 + \frac{0.0266}{s}$$

$$G_{O70Lead}(s) = 14 * G_{C70}(s) * G_{L70}(s) = \frac{5.414s+0.2365}{37.89s^3+24.69s^2+s}$$

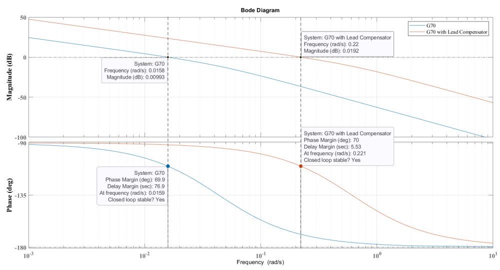

Figure 1.1.4: Bode Plot of $G_{O70lead}(s)$

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1.2 Task 2

Transfer function of Tangent Method is used to design the controller using Zeigler tuning rules, TSum rules and opelt tuning rules. Delay time $T_u = 13s$, rise time $T_a = 198s$ and process gain $K_s = 0.635$
Transfer Function :

$$G(s) = \frac{0.635}{(3187.8s^2+161.35s+1)}$$

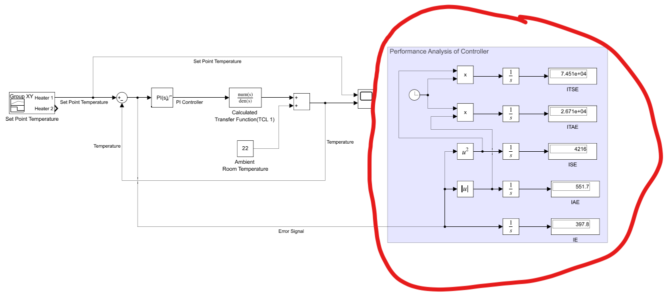
Table 1.2.1: Tuning Methods

Tuning Method	K_r (Propotional Gain constant)		T_I (Integral Time constant)	
Zeigler	$\mathrm{K}_r = \frac{0.9T_a}{K_s.T_u} = \frac{(0.9)(198)}{(0.635)(13)}$	21.6	$\mathrm{T}_I = 3.33T_u = (3.33)(13)$	43.29
TSum	$\mathrm{K}_r = \frac{1}{K_s} = \frac{1}{0.635}$	1.6	$\mathrm{T}_I = 0.7T_\Sigma = (0.7)(13 + 198)$ f	147.7
Opelt	$\mathrm{K}_r = \frac{0.8T_a}{K_s.T_u} = \frac{(0.8)(198)}{(0.635)(13)}$	19.2	$\mathrm{T}_I = 3T_u = (3)(13)$	39

1.3 Task 3

$T_\Sigma = T_1 + T_2$

Implement the PI controllers identified above in the Matlab/SIMULINK file with the transfer function from TCL 1 and test their performance.



See below

Figure 1.3.1: System with controller: Simulation Setup

- A feedback of output temperature is compared with the setpoint temperature, difference of these two is given to PI controller to get heater1%
- To compare the system behaviour the output variable (temperature1°C) results are plotted with controller's of 3 different tuning methods.
- PI Controller Block setting : Anti winding method is clamping, Continuous, form is parallel, saturation(0% and 100%), Tuning method is Transfer function based. very good
- Once the set point temperate reaches zero, the heater temperature is reaching ambient temperature.
- settling tine + /- 5% (35.65°C - 34.35°C)

- To evaluate the performance of the PI controller, it is crucial to assess various parameters such as rise time, peak time, overshoot ratio, damping ratio, and settling time. However, as these metrics may not be encompassed by TSUM, more precise parameters are essential for a thorough analysis. In this context, we consider IE (Integral Error), IAE (Integral Absolute Error), ISE (Integral Square Error), ITAE (Time Integral Absolute Error), and ITSE (Time Integral Square Error). Ideally, for a controller to be deemed optimal, it should exhibit lower values across all the specified parameters.
- Ziegler and Opelt tuning rules closely match the desired controller parameters. Conversely, TSUM exhibits a significant margin of error and achieves steady state more gradually when compared to the other tuning methods fig 1.3.2.

Table 1.3.1: Simulation Results of 35°C

Parameters	Ziegler	TSum	Opelt
Rise Time	56.5s	NA	56.2s
Peak Time	79.7s	NA	79.7s
Overshoot Ratio	0.1238 = 12.38%	NA	0.1569 = 15.69%
Delay Ratio	0.2484 = 24.84%	NA	0.2058 = 20.58%
Settling Time	174.02s	NA	171.69s
IE	397.8	1918	412.1
IAE	551.7	1918	557.4
ISE	4216	1.4×10^4	4211
ITAE	2.67×10^4	2.544×10^5	2.939×10^4
ITSE	7.451×10^4	9.288×10^5	7.509×10^4

Very good

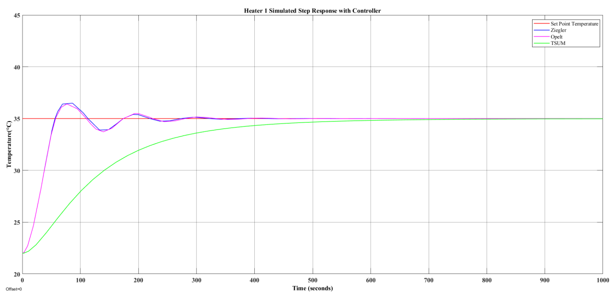


Figure 1.3.2: Heater1 Step Response with controller: Simulation

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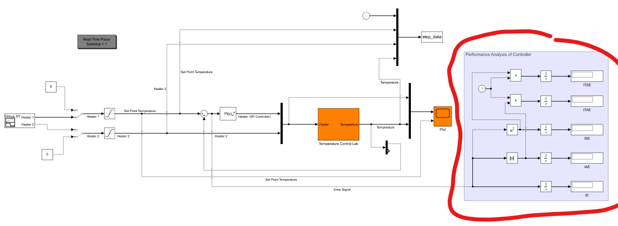
2 Practical part

Determination and validation of controller design strategies without prior model identification.

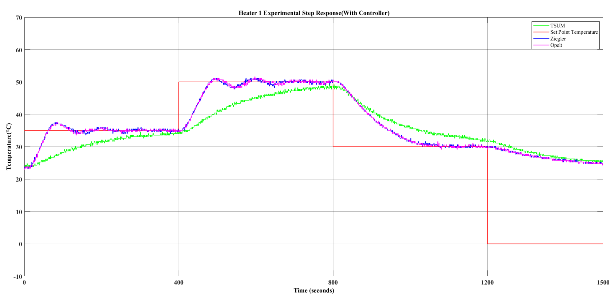
2.1 Task 1

Utilizing the values obtained from the tuning rules table:1.2.1 for PI controller design and implementing them in the experimental setup fig 2.1.1, the resulting outcomes are presented as follows fig: 2.1.2.



good idea, but a bit to much IE and/or IAE/ISE would be sufficient

Figure 2.1.1: System with controller: Experimental Setup



this is already a very good Illustration of a set point change from 35°C to 50°C

Figure 2.1.2: Heater1 Step Response with controller: Experimental

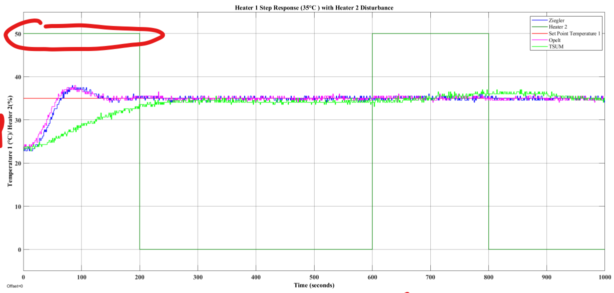
2.2 Task 2

Implement and test the controller for the Heater-Sensor-System by :

2.2.1 Disturbing the system via the other heater

Introducing Heater 2 involves applying input at arbitrary positions. Specifically, opted for 50% input for Heater 2 during two distinct time intervals, namely 0-200s and 600-800s. This strategic selection aims to gain insights into the performance of the Heater 1 system, both during transient states and steady states, under the influence of Heater 2 input as shown in fig: 2.2.1 and table: 2.2.1

this one is not meaningful. disturbance should activate when steady state is reached



very good!

Figure 2.2.1: Heater1 Step Response with Heater2 as a disturbance

(as you have done with)

Table 2.2.1: Experimental Results with Heater2 as disturbance

Parameters	Ziegler	TSum	Opelt
Rise Time	64.87s	NA	59.54s
Peak Time	89.48s	NA	88.82s
Overshoot Ratio	0.2483 = 24.83%	NA	0.2483 = 24.83%
Delay Ratio	0.5067 = 50.67%	NA	0.5067 = 50.67%
Settling Time	259.148s	NA	290.41s
IE	405.5	1514	315.6
IAE	815	1953	765.4
ISE	5354	1.164×10^4	4162
ITAE	1.324×10^5	4.49×10^5	1.501×10^5
ITSE	1.699×10^5	9.55×10^5	1.483×10^5

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2.2.2 Changing the set point of the heater-sensor-system:

To assess the system's performance under varying set point input temperatures, experiments were conducted with set points of 35°C and 55°C. The respective outcomes for all three controllers are visually represented in the figure: 2.2.2 and figure: 2.2.3 and summarized in the accompanying table: 2.2.2 and table: 2.2.3

actually you do the wanted set-point change already in Fig. 2.1.2.

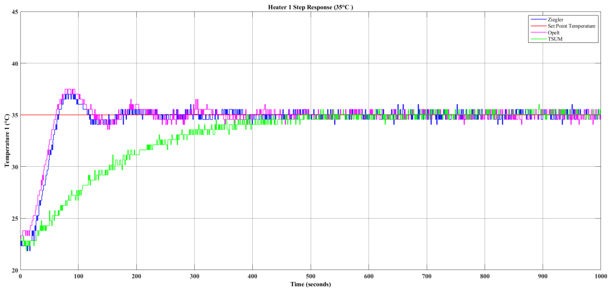

Figure 2.2.2: Heater1 Step response with controller: Experimental(35°C)

Table 2.2.2: Experimental Results of 35°C

Parameters	**Ziegler**	**TSum**	**Opelt**
Rise Time	61.279s	NA	61.49s
Peak Time	83.66s	NA	85.94s
Overshoot Ratio	$0.2075 = 20.75\%$	NA	$0.2075 = 20.75\%$
Delay Ratio	$0.4096 = 40.96\%$	NA	$0.409 = 40.9\%$
Settling Time	317.51s	NA	262.21s
IE	418.7	1918	359.6
IAE	867.9	2094	794.8
ISE	5320	1.479×10^4	4501
ITAE	1.628×10^5	3.223×10^5	1.398×10^5
ITSE	1.8847×10^5	1.137×10^5	1.514×10^5

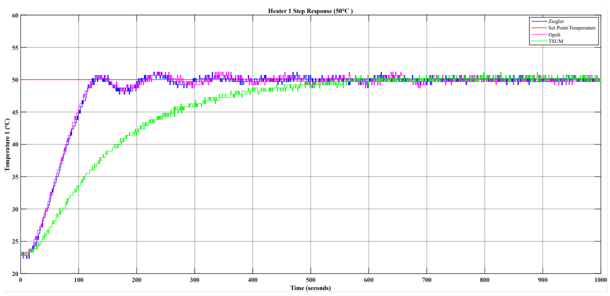

Figure 2.2.3: Heater1 Step response with controller: Experimental (50°C)

Table 2.2.3: Experimental Results of 50°C

Parameters	Ziegler	TSum	Opelt
Rise Time	81.473s	NA	81.23s
Peak Time	95.218s	NA	100.64s
Overshoot Ratio	0.078 = 7.8%	NA	0.078 = 7.8%
Delay Ratio	1= 100%	NA	1.418 = 141.8%
Settling Time	266.4s	NA	280.12s
IE	1928	4361	1853
IAE	2220	4547	2197
ISE	3.855×10^4	7.1×10^4	3.688×10^4
ITAE	2.418×10^5	6.769×10^5	2.623×10^5
ITSE	1.289×10^6	5.301×10^6	1.229×10^6

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2.3 Task 3

Interpret the experimental results and compare the performance of the controllers to each other.

- Ziegler and Opelt controllers are highly suitable, ensuring faster attainment of the desired set point temperature with minimal integral error.
- TSUM exhibits a slower response with a higher integral error but distinguishes itself by avoiding overshoot during operation.
- All three systems successfully maintained the reference temperature during changes in the set point of the heater sensor system.
- Ziegler and Opelt displayed effective performance under Heater 2 disturbance, exhibiting stability in both transient and steady states of the step response. However, TSUM controller showed a slight deviation from the reference at the steady state of the step response.

In summary, Ziegler and Opelt controllers excel in quick response, while TSUM provides stable operation without overshoot, catering to distinct system preferences.

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Style: 2/4
to many pages
Images to short

$\boxed{\text{extra points on understanding + 2}}$

Σ 39/40
Very good

mark 1.0

Bibliography

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[3] Handout TCL 2.