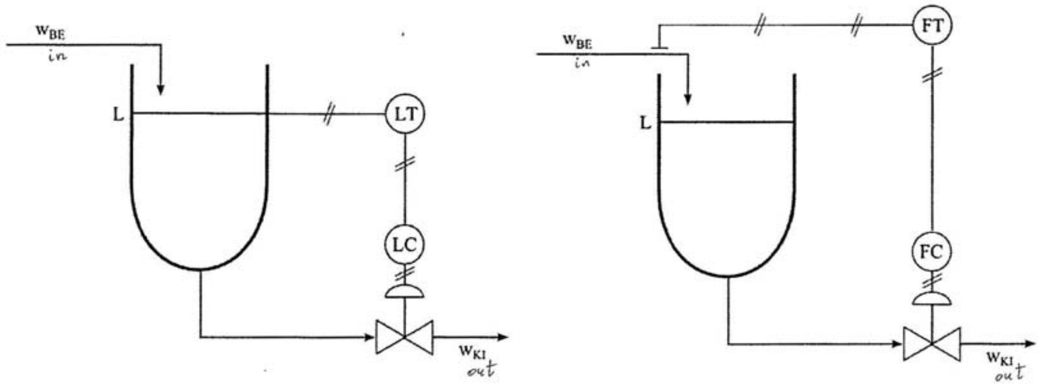
Process control laboratory practice
Cascade control

INTRODUCTION

Feed-forward control is applied in order to accelerate the reaction of the controllers to some disturbances by catching them even before reaching the controlled process. In feed-forward control the disturbance is measured and is compared to a feed-forward set point signal to produce an error signal that the feed-forward controller FFC works up.

Example: Level is to be kept constant in a vessel. The controlled variable is the liquid level, the outlet flow is manipulated, and the inlet flow is the disturbance.
In the case of feed-back control the level is measured.
In the case of feed-forward control the inlet flow rate is measured.



Feed-back level control	Feed-forward level control
LT: level transmitter	FT: Flow rate transmitter
LC: level controller	FC: Flow rate controller

Figure 1. Level control with feed-back and feed-forward loops

Properties of well working feed-forward control (with contrast to feed-back control):

1. Effects of known and measured disturbance can be cancelled out simultaneously with a properly selected modified variable so that the controlled variable remains unaffected without fluctuation. (There is always fluctuation in a feed-back loop.)
2. For this aim, the mathematical model of the process and the other elements in the loop must be exactly known. (Approximate knowledge is enough for a feed-back loop.)
3. A properly set feed-forward loop is always stable. (Feed-back loops can be unstable.)
4. Only the known and measured disturbance can be cancelled with feed-back loop. (All the known and unknown disturbances can be cancelled in a feed-back loop.)

Feed-forward control is applied to exceedingly slow processes, with large time constants, in order to prevent the controlled variable's deviation from the set point. That would be inevitable with feed-back control.

However, feed-forward control is almost always combined with feed-back in order to cancel out unforeseen disturbances.

General block scheme:

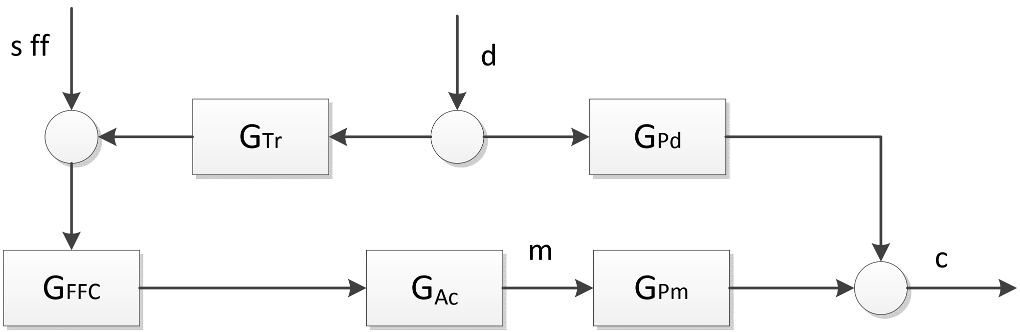


Figure 2. Block scheme of feed-forward control

Tuning

The controller's gain A_C can and should be set irrespectively to the dynamics of the controller because there is just one value that eliminates the effect of the measured disturbance, as follows.

Suppose the gain of the process respect to the disturbance is A_d.

Suppose the gain of the process respect to the manipulated variable is A_m, the gain of the transmitter is A_{Tr}, and the gain of the actuator is A_{Ac}. Then

$$\hat{c}_\infty = \left(A_d - A_{Tr} \cdot A_C \cdot A_{Ac} \cdot A_m\right) \cdot \hat{d}$$

In order to eliminate the change in the new steady state, i.e. get $\hat{c}_\infty = 0$, we have to select A_C so that $A_d - A_{Tr} \cdot A_C \cdot A_{Ac} \cdot A_m = 0$, i.e.

$$A_C = \frac{A_d}{A_{Tr} \cdot A_{Ac} \cdot A_m}$$

The same equation must be valid for the transfer functions in order to perfectly eliminate ($\hat{c}(t) = 0$) the effect of any change in the disturbance:

$$G_{FCC} = \frac{G_{Pd}}{G_{Tr} \cdot G_{Ac} \cdot G_{Pm}}$$

If such a controller can somehow be constructed, for that aim we ought to know precisely the dynamic behavior of all the elements in the system. Usually this is not the case.

If all the elements are proportional then a P controller with A_C as computed above will do.

In the general case the constructability of a controller depends on the ratio of time constants.

If the process reacts slower to d than to m then a good feed-forward control can be constructed. In this case the control can be improved by connecting a so-called lead-lag element after the controller. This has two time parameters: T_1 and T_2, and its effect is

$$\hat{y}(t) = \left(1 + \frac{T_2 - T_1}{T_2} e^{\frac{t}{T_2}}\right) \cdot \hat{x}(t)$$

The lead-lag element can be modeled by a consecutive connection of a PT1 and a PT. Parameter P_D of PT takes the role of T_2, whereas parameter T of PT1 takes the role of T_1.

If, on the other hand, the process reacts faster to d then to m, then good feed-forward control cannot be achieved.

Tuning consists of two, well separable, steps:

1. Set the controller's gain (A_C).
2. Set the controller's time constants (T_1 and T_2).

For step 1 one measures the gains from d to c and from m to c. Denote these gains by AA_d and AA_m, then for cancelling the effect of d we want

$$\hat{c}_\infty = \left(AA_d + A_C \cdot AA_m\right) \cdot \hat{d} = 0$$

Thus we have

$$A_C = -\frac{AA_d}{AA_m}$$

This value is independent on the dynamics. If not this value is applied then the effect of disturbance is never cancelled.

In step 2, the time constants is suggested (by F. G. Shinskey) to set so that positive and negative deviations cancel out each other. This is discussed in the next figure.

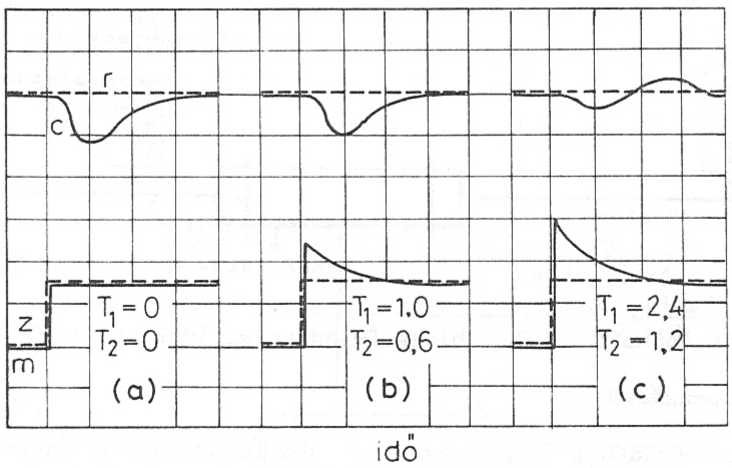


Figure .3. Setting T_1 and T_2 by Shinskey. (a) wrong, (b) not enough, (c) good

The time constants are to be set so that ISE must be at minimum. This is a bivariate optimization problem.

Aim of the practice

1. Approximately optimal tuning of feed-back controller.
2. Tuning the feed-back controller with cycling.
3. Comparison of the 3 systems: feed-back, feed-forward, and combined, with 3 kinds of disturbance: known, unknown, and both. This is altogether 9 cases. Compare control time, overshoot, steady offset, and integrated square error (ISE).

Applied model

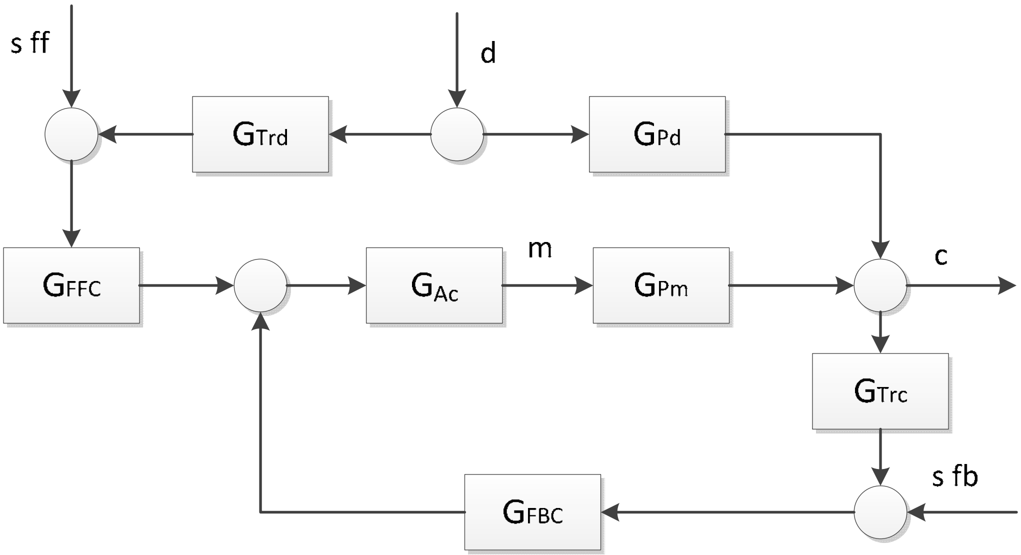


Figure 4. Feed-forward combined with feed-back

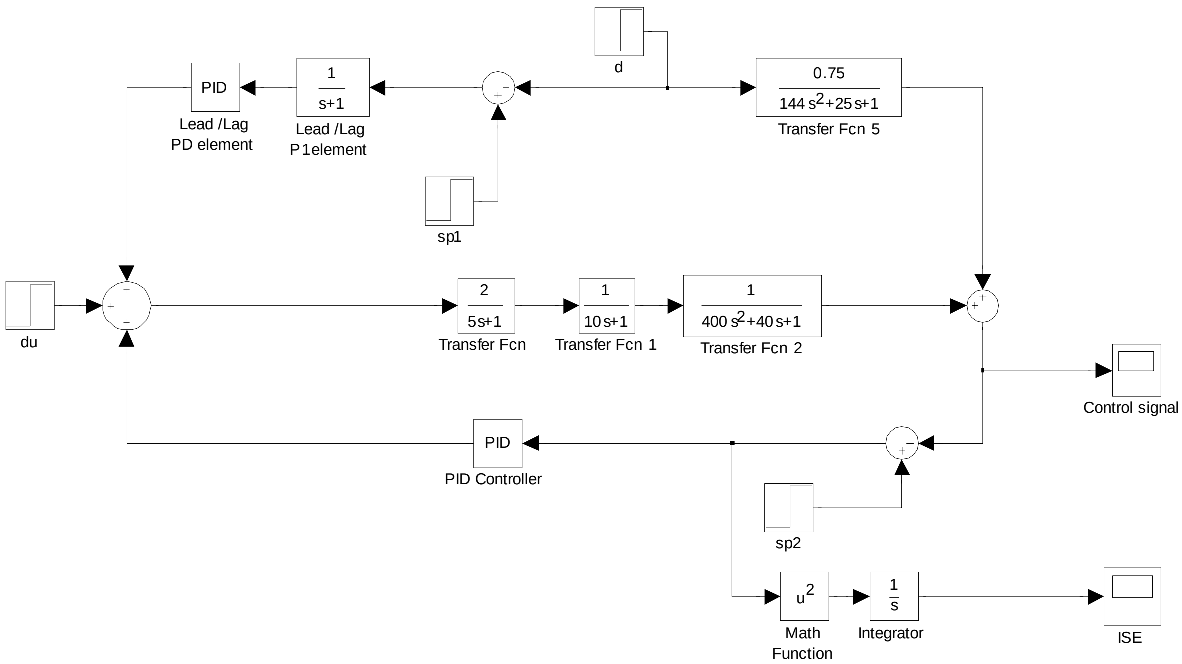


Figure 5. Model applied in Simulink

sp1: set point signal, feed forward loop

sp2: set point signal, feedback loop

d: disturbance, measured

du: disturbance, unknown

We suppose that values of T_1 and T_2 are constrained in the range 1.0 to 50.0 (!)

Tuning the feed-forward controller

1.Static (gain) setting

1. Let m=0 and d=0.1. Cut the branch to the controller and measure the response of c. Calculate AA_d.
2. Let d=0 and m=0.1. Measure the response of c. Calculate AA_m.
3. Calculate A_C (=A_{LL}) and set the P1 member of the controller cascade accordingly.
4. Let m=0 and d=0.1. Switch on all the connections of the feed-forward system (without feed-back), and check is the disturbance is cancelled.

2. Dynamic identification and initial tuning

1. Let m=0 and d=0.1. Plot the response of c in time. It will probably deviate from zero in one direction only and **attenuates to zero**.
2. Read the **time moment** of the maximum. This is denoted by t_p.
3. Let the gain of the PD member of the feed-forward controller be 1, and let it always so! Let the gain of the P1 member of the feed-forward controller be the calculated A_{LL}. Let T_1=1.5t_p, and T_2=0.7t_p .
4. Plot the response of c in time. If you are lucky, the curve intersects the t axis once. If not, exchange the two time constant values, and repeat the measurement. You must get a good curve. If not, find one by small changes in T1 and T2.

3. Optimal tuning

We suppose that values of T_1 and T_2 are constrained in the range 1.0 to 50.0 (!)

A near optimal tuning can be found so that the problem is transformed to monovariate optimization by applying Shinsky's idea, as follows.

1. Keep one of the time constants fixed while changing the other one **in small steps** till the areas of the two deviations become approximately equal. This can be checked by comparing the steps of the ISE curve.
2. Read and take note of ISE and the time constants.
3. Modify **a little** the value of the time constant hitherto kept fixed, and repeat step 1.
4. Read and take note of ISE and the time constants. If ISE increased then modify the just modified time constant in the reverse direction, and repeat step 1. If ISE decreased then repeat step 3 again in the already determined direction, and so on.
5. If one of the time constants has reached its border (1 or 50) then modify the other on only, irrespectively to the Shinsky criterion till you find a minimum.

Tuning the feed-back controller

Temporarily cut the command connection from the feed-forward controller. Switch on the command connection of the feed-back controller. Tune the feed-back controller by cycling.

Names	Feed-forward control	Date

1. Tuning feed-forward controller

1.1. Static setting

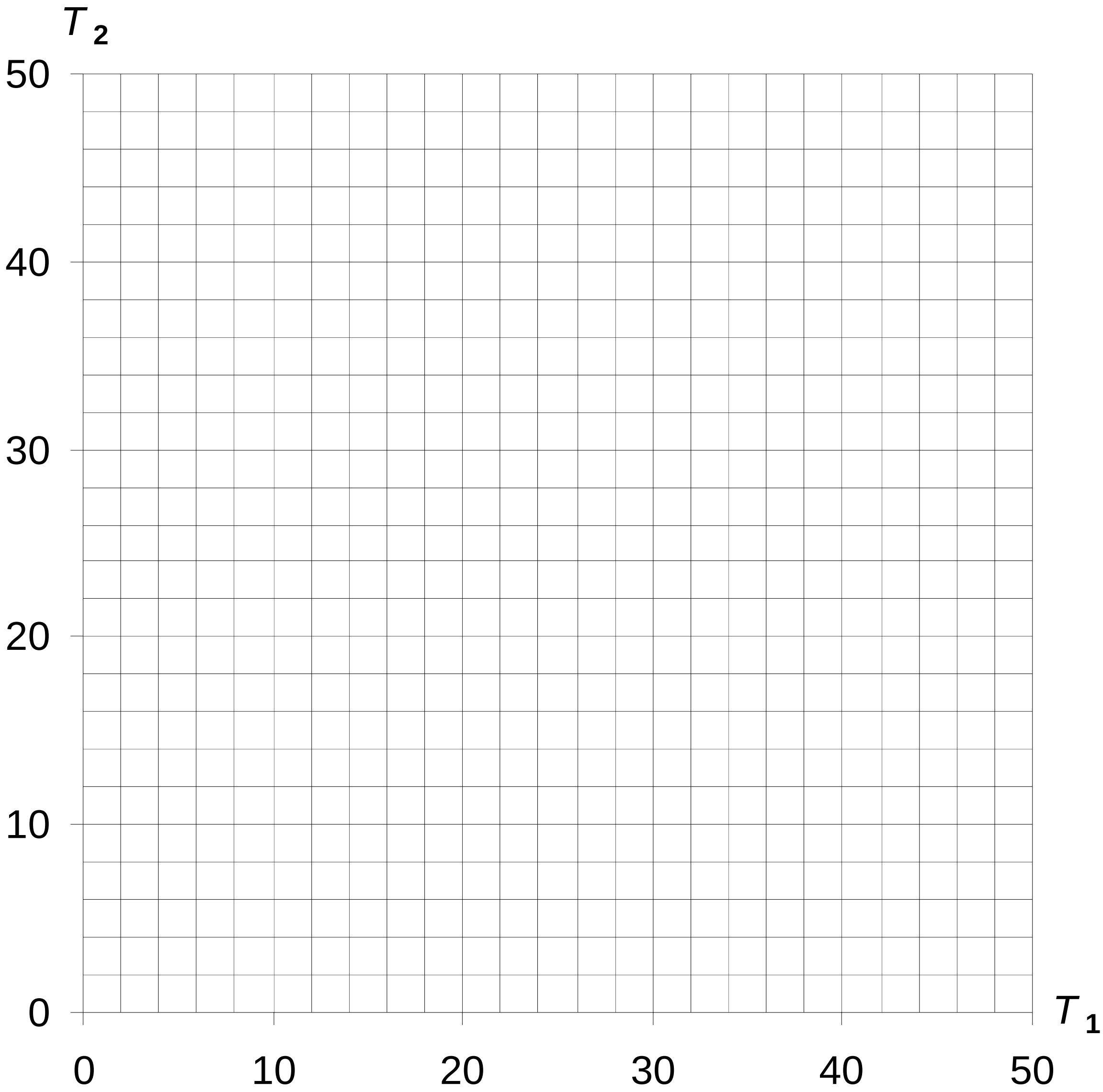
- d ………..
- c response ………..
- AA_d ………..
- du ………..
- c response ………..
- AA_m ………..
- A_C (=A_{LL}) ………..

1.2. Dynamic setting

- t_p ………..
- Initial time constants T_1 ……….. T_2 ………..
- Points during optimization

	T_1 (s)	T_2 (s)	*ISE*
1			
2			
3			
4			
5			
6			
7			
8			

- Optimal values T_1 ……….. T_2 ………..



2. Tuning feed-back PI controller

2.1. Critical data

- Critical gain ………..
- Critical period ………..

2.2. Set data

- Gain ………..
- Integration time ………..

3. Evaluation, comparison

System	disturbance		*ISE*	$T_{control}$	overshoot	steady offset
	d	*du*				
Feed-forward	0.1	0				
	0	0.1				
	0.1	0.1				
Combined	0.1	0				
	0	0.1				
	0.1	0.1				
Feed-back	0.1	0				
	0	0.1				
	0.1	0.1				