Chapter 8

Various control methods and control structures

This chapter describes various control methods and control structures and for industrial applications. Most of the structures involve one or more PID control loops.

8.1 Feedforward control

8.1.1 Introduction

We know from previous chapters that feedback control can bring the process output variable to or close to the setpoint. Feedback control is in most cases a sufficiently good control method. But improvements can be made, if required. A problem with feedback is that it is no adjustment of the control variable before the control error is different from zero, since the control variable is adjusted as a function of the control error. This problem does not exist in *feedforward control*, which may be used as the only control method, or, more typically, as a supplement to feedback control.

In feedforward control there is a *coupling from the setpoint and/or from the disturbance directly to the control variable*, that is, a coupling from an input signal to the control variable. The control variable adjustment is not error-based. In stead it is based on knowledge about the process in the form of a mathematical model of the process and knowledge about or measurements of the process disturbances.

Perfect or ideal feedforward control gives zero control error for *all types of signals* (e.g. a sinusoid and a ramp) in the setpoint and in the disturbance. This sounds good, but feedforward control may be *difficult to implement* since it assumes or is based on a mathematical process model and that all variables of the model at any instant of time must have known values through measurements or in some other way. These requirements are never completely satisfied, and therefore in practice the control error becomes different from zero. We can however assume that the control error becomes smaller with imperfect feedforward control than without feedforward control.

If feedforward control is used, it is typically used together with feedback control. Figure 8.1 shows the structure of a control system with both feedforward and feedback control. The purpose of feedback control is to reduce the control error due to the inevitable imperfect feedforward control. Practical feedforward control can never be perfect, because of model errors and imprecise measurements.

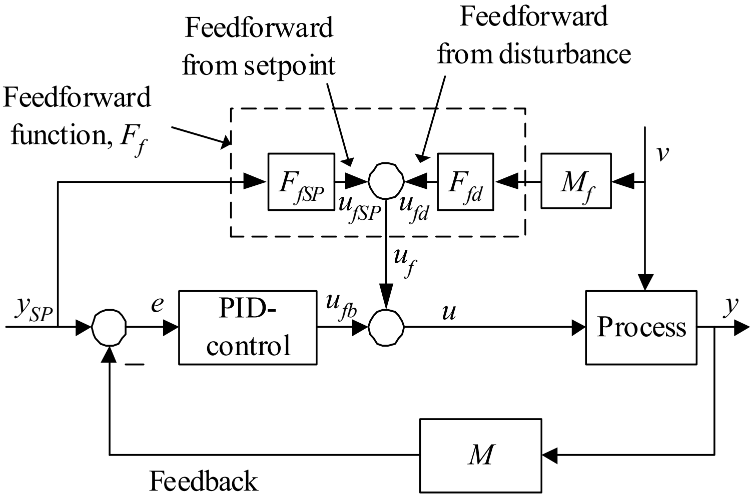

Figure 8.1: Control system with both feedforward and feedback control

One interpretation of feedforward control is that it introduces an artificial connection from the disturbance to the process output variable. The purpose of this artificial connection is to counteract the natural connection (from the disturbance to the process output variable).

The feedforward function F_f, which usually consists of a sum of partial functions F_{fSP} and F_{fd} as shown in Figure 8.1, can be developed in several ways:

- From a differential equations process model
- From a transfer functions process model
- From experimental data. This method is model-free.

Method one and three are described in the following sections as they are assumed to be the most useful in practical cases.

Using feedforward together with feedback does not influence the stability of the feedback loop because the feedforward does not introduce new dynamics in the loop.

8.1.2 Designing feedforward control from differential equation models

The feedforward function F_f can be derived quite easily from a differential equations model of the process to be controlled. The design method is to *solve for the control output variable in the process model with the setpoint substituted for the process output variable* (which is the variable to be controlled). The model may be linear or non-linear.

Example 8.1 ***Feedforward control of a thermal process***

Figure 8.2 shows a heated liquid tank where the temperature T shall be controlled using feedback with PID controller in combination with feedforward control. The symbol Y represents calculations (specified elsewhere). We assume the following process model, which is based on energy balance:

$$c\rho V\dot{T}(t) = \underbrace{K_h u(t)}_{P} + cw\left[T_{in}(t) - T(t)\right] + U\left[T_e(t) - T(t)\right] \tag{8.1}$$

where T [K] is the temperature of the liquid in the tank, T_{in} [K] is the inlet temperature, T_e [K] is environmental temperature, c [J/(kg K)] is specific heat capacity, w [kg/s] is mass flow (same in as out), V [m^3] is the liquid volume, ρ [kg/m^3] is the liquid density, U [(J/s)/K] is the total heat transfer coefficient, $P = K_h u$ [J/min] is supplied power via heating element where K_h is a parameter (gain) and u [%] is the control signal applied to

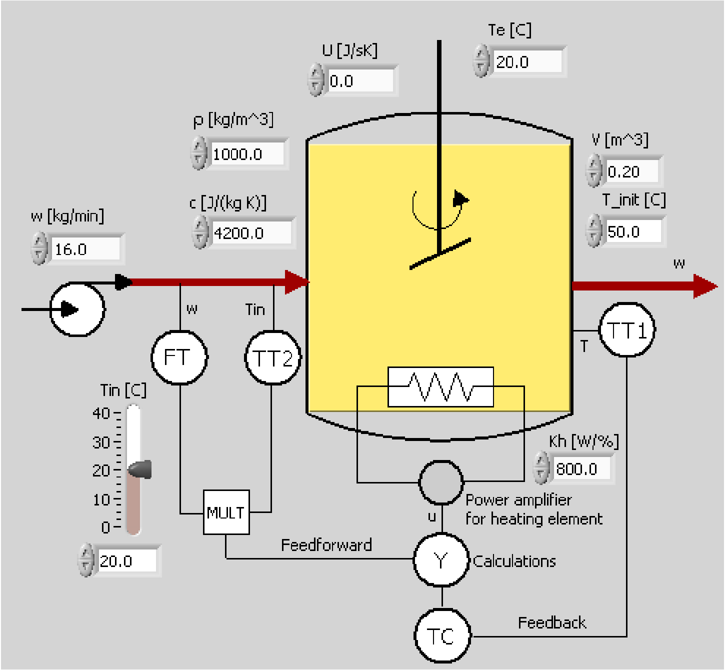

Figure 8.2: Example 8.1: Heated liquid tank where the temperature T shall be controlled with feedforward control in addition to feedback control.

the heating element. $c\rho VT$ is the (temperature dependent) energy of the liquid in the tank. We can consider T_{in} and T_e as disturbances, but the derivation of the feedforward function F_f is not dependent of such a classification. In the following we assume for simplicity that the heat transfer coefficient U is zero so that the heat transport through the walls is zero.

Now, let us derive the feedforward function from the process model (8.1). First, we substitute the temperature T by the temperature setpoint T_{SP}:

$$c\rho V\dot{T}_{SP}(t) = K_h u(t) + cw\left[T_{in}(t) - T_{SP}(t)\right] \tag{8.2}$$

We *solve (8.2) for the control variable* u to get the feedforward control variable u_f:

$$\begin{aligned} u_f(t) &= \frac{1}{K_h}\left\{c\rho V\dot{T}_{SP}(t) - cw\left[T_{in}(t) - T_{SP}(t)\right]\right\} && (8.3) \\ &= \underbrace{\frac{1}{K_h}\left[c\rho V\dot{T}_{SP}(t) + cwT_{SP}(t)\right]}_{u_{fSP}} + \underbrace{\frac{1}{K_h}\left[-cwT_{in}(t)\right]}_{u_{fd}} && (8.4) \end{aligned}$$

We see that calculation of feedforward control signal u_f requires measurement or knowledge of the following five quantities: c, ρ, V, h, w,

K_h and T_{in}, in addition to the setpoint time-derivative, $\dot{T}_{SP}$. Figure 8.2 indicates that mass flow w and inlet temperature T_{in} are measured.

If the setpoint is assumed to be constant, which is typically the case, the time derivative of T_{SP} is zero, and $u_f(t)$ becomes

$$u_f(t) = \frac{cw}{K_h}\left[T_{SP}(t) - T_{in}(t)\right] \tag{8.5}$$

The following two cases are simulated: Temperature control *without* and *with feedforward control*. In both cases there is feedback control with PI controller with parameters $K_p = 3.5$ and $T_i = 6$ min. The setpoint T_{SP} is constant, but there are variations in the disturbance T_{in} (the inlet temperature). We see that the control variable compensates immediately for the variations in the disturbance, which is due to the direct control action inherent in feedforward control. Figure 8.3 shows the simulated responses without feedforward control, and Figure 8.4 shows the responses with feedforward control. The control error is in principle zero at every instant of time with feedforward control, while it is nonzero without feedforward until the feedback control has compensated for the disturbance

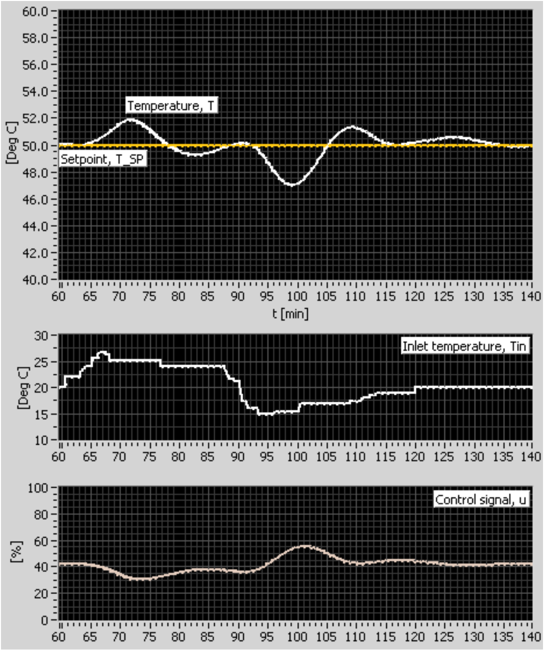

Figure 8.3: Example 8.1: Responses in the temperature control system without feedforward control, but with feedback control

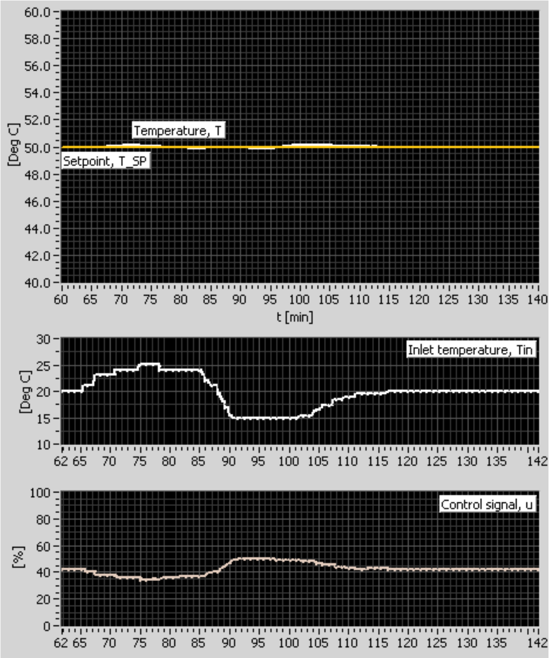

Figure 8.4: Example 8.1: Responses in the temperature control system with feedforward control, in addition to feedback control

in steady state.[1]

[End of Example 8.1]

8.1.3 Designing feedforward control from experimental data

Feedforward control can be designed from experimental data as follows:

- Decide a proper set of N different values of the disturbance, v on which the feedforward control will be based, for example $N = 6$ different values of the disturbance.
- For each of these N distinct disturbance values, find (experimentally or by simulation) the value of the control signal u which corresponds to zero steady state control error, which can be obtained with PI or PID feedback control (typically feedback control is used together

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[1] In this simulaton the control error is a little different from zero due to numerical inaccuracies in the way I have implemented the simulator.

with feedforward control, so no extra effort is needed to run the feedback control here).

- The set of N corresponding values of v and u can be represented by a table, cf. Table 8.1.

u	v
u_1	v_1
u_2	v_2
u_3	v_3
u_4	v_4
u_5	v_5
u_6	v_6

Table 8.1: N corresponding values of v and u

or in a coordinate system, cf. Figure 8.5.

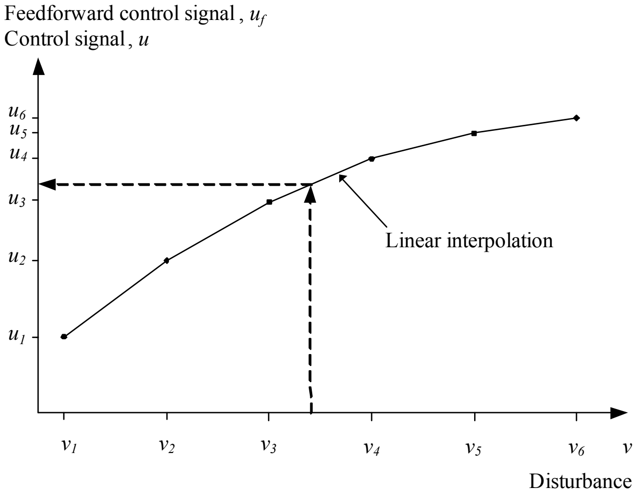

Figure 8.5: Calculation of feedforward control signal from known disturbance value

- For any given (measured) value of the disturbance, the feedforward control signal u_f is calculated using interpolation, for example linear interpolation as shown in Figure 8.5. In practice, this linear interpolation can be implemented using a table lookup function.[2]

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[2] Both MATLAB/SIMULINK and LabVIEW have functions that implement linear interpolation between tabular data.

Note: This feedforward design method is based on *steady state* data. Therefore, the feedforward control will not be ideal or perfect. However, it is easy to implement, and it may give substantial better control compared to only feedback control.

Example 8.2 *Temperature control with feedforward from flow*

Figure 8.6 shows a lab process consisting of a heated air tube where the air temperature will be controlled. The control signal adjusts the power to the heater. The air temperature is measured by the primary Pt100 element. The feedback PID control is based on this temperature measurement. (The control system is implemented with a LabVIEW program running on a laptop PC.)

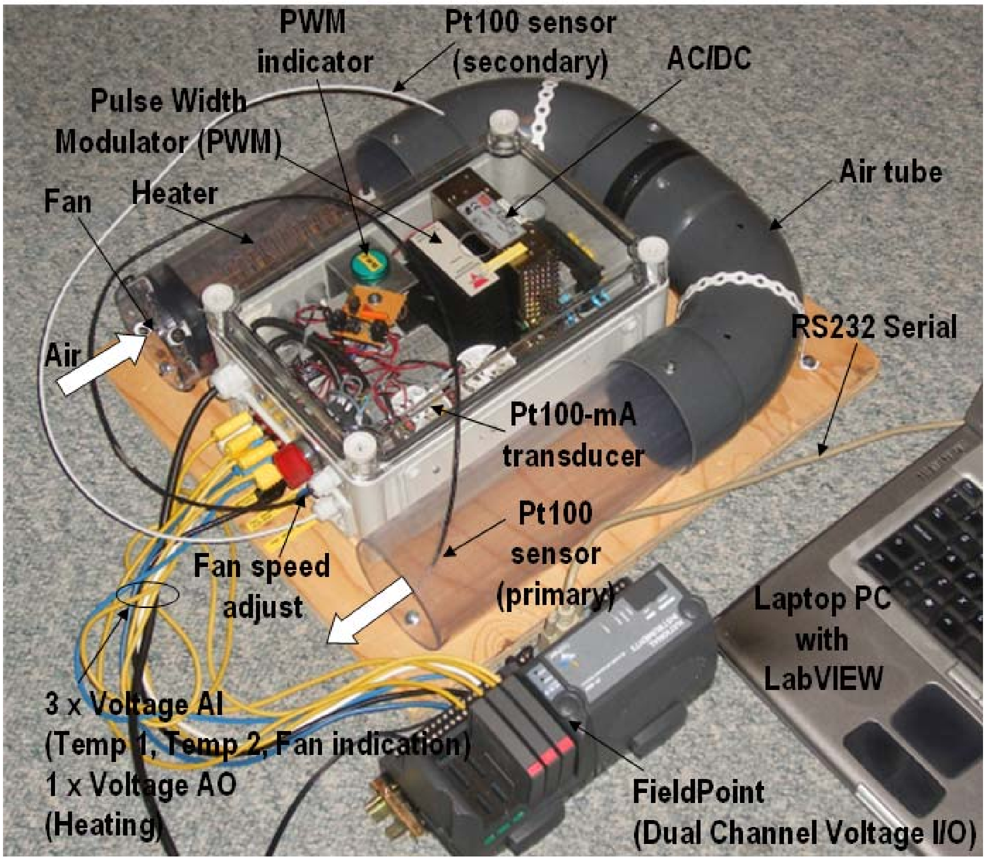


Figure 8.6: Example 8.2: A lab process consisting of a heated air tube where the air temperature will be controlled.

Variations of the air flow act as disturbances to the process. The feedback controller tries to compensate for such variations using the temperature measurement. Can we obtain improved control by also basing the control signal on measured air flow, which is here available as the fan speed indication? First, ordinary PID control without feedforward is tried. The fan speed was changed from minimum to maximum, and then back again. The temperature setpoint was 40 %. Figure 8.7 shows the fan speed and the response in the temperature (which is represented in % with the range [0–100%] corresponding to [20–70^{o}C]). The maximum control error was 1.0 %.

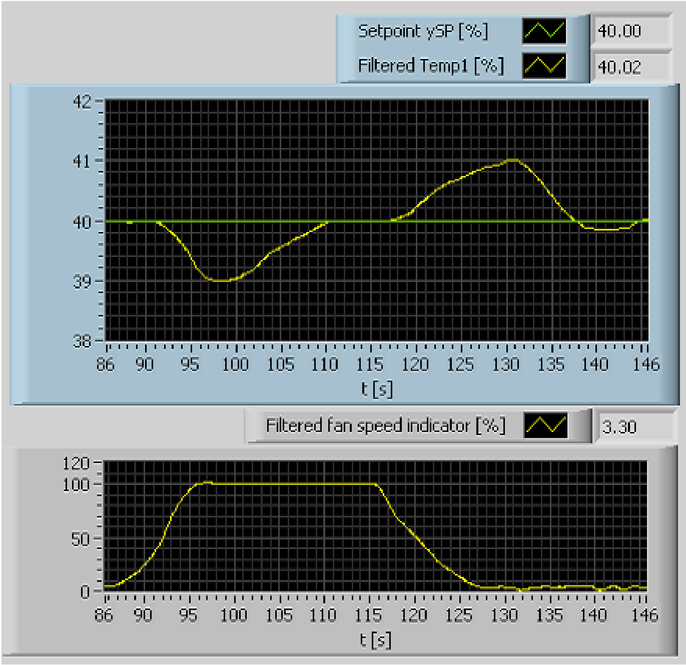
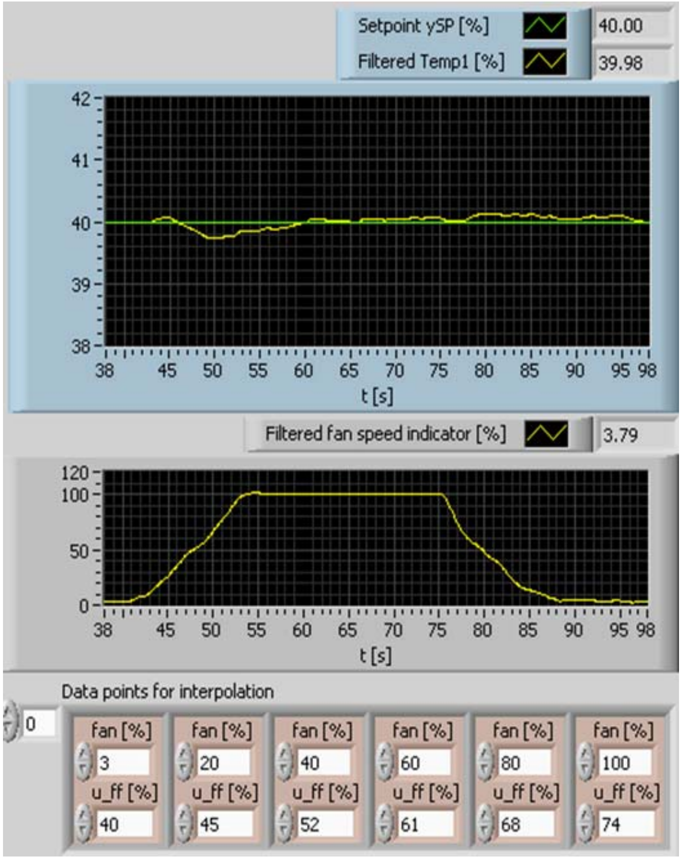


Figure 8.7: Example 8.2: The response in the temperature after a change in the fan speed. Only feedback control (no feedforward) control is used.

Will there be any improvement by using feedforward control from the fan speed (air flow)? A number of corresponding values of fan speed and control signal was found experimentally. The feedforward control signal, u_f, was calculated by linear interpolation with Interpolate 1D Array function in LabVIEW, and was added to the PID control signal to make up the total control signal: $u = u_{PID} + u_f$. Figure 8.8 shows the the fan speed and the response in the temperature. Also, the set of 6 corresponding values of control signal and fan speed, on which the feeedforward control signal is based, is shown. In this case the maximum control error was 0.27,



Setpoint ySP [%] 40.00

Filtered Temp1 [%] 39.98

Filtered fan speed indicator [%] 3.79

Data points for interpolation

0

fan [%]	3	20	40	60	80	100
u_ff [%]	40	45	52	61	68	74

Figure 8.8: Example 8.2: The response in the temperature after a change in the fan speed. Feedforward from fan speed (air flow) is used together with feedback control.

which is a large improvement compared to using no feedforward control!

[End of Example 8.2]

8.2 Cascade control

From earlier chapters we know that a control loop compensates for disturbances so that the control error is small despite the disturbances. If the controller has integral action the steady-state control error is zero. What more can we wish? In some applications it may be desirable if the transient time progression of the error is faster, so that e.g. the IAE index, cf. Section 5.6, is smaller. This can be achieved by *cascade control*, see