Chapter 4

Experimental tuning of PID controllers

4.1 Introduction

This chapter describes several methods for experimental tuning of controller parameters in P-, PI- and PID controllers, that is, methods for finding proper values of K_p, T_i and T_d. The methods can be used experimentally on physical systems, but also on simulated systems.

The methods described can be applied only to processes having a time delay or having dynamics of order higher than 3. Here are a few examples of processes (transfer function models) for which the method can *not* be used:

$$H(s) = \frac{K}{s} \qquad \text{(integrator)} \tag{4.1}$$

$$H(s) = \frac{K}{Ts+1} \qquad \text{(first order system)} \tag{4.2}$$

$$H(s) = \frac{K}{(\frac{s}{\omega_0})^2 + 2\zeta\frac{s}{\omega_0} + 1} \qquad \text{(second order system)} \tag{4.3}$$

Controller tuning for processes as above can be executed with a transfer function based method, cf. Chapter 7.

The methods described in this chapter can be regarded as general methods since their procedure is the same, regardless the dynamic properties of the process to be controlled. There are processes for which the methods does not fit well, for example a first order process with a time delay much larger than the time constant. Chapter 7 describes tuning methods which are based on the given dynamic properties of the process as expressed in a transfer function model, and the PID parameters are then tailored for this process. You can expect that such model-based tuning methods will give the control system better performance (as faster control) than if the controller was tuned with a general tuning method. Despite this, the general tuning methods are important because they have proven to work well and because they are simple to use (they do not require an explicit process model).

4.2 A criterion for controller tuning

A reasonable criterion for tuning the controller parameters is that the control system has *fast control with satisfactory stability.* These two requirements – fast control and satisfactory stability – are in general contradictory: Very good stability corresponds to sluggish control (not desirable), and poor stability (not desirable) corresponds to fast control. A tuning method must find a compromise between these two contradictory requirements.

What is meant by satisfactory stability? Simply stated, it means that the response in the process output variable converges to a constant value with satisfactory damping after a time-limited change of the setpoint or the disturbance. Satisfactory damping can be quantified in several ways. Ziegler and Nichols [20] who published famous tuning rules in the 1940s claimed that satisfactory damping corresponds to an amplitude ratio of approximately 1/4 between subsequent peaks in the same direction (due to a step disturbance in the control loop), see Figure 4.1:

$$\frac{A_2}{A_1} = \frac{1}{4} \tag{4.4}$$

Ziegler and Nichols used this as a stability criterion when they derived their PID tuning rules. However, there is no guaranty that the actual amplitude ratio of a given control system becomes 1/4 after tuning with one of the Ziegler and Nichols' methods, but it should not be very different from 1/4.

If you think that the stability of the control loop becomes too bad or too good, you can try to adjust the controller parameters. The first aid, which may be the only adjustment needed, is to adjust the controller gain K_p as follows:

- Too bad stability: Decrease K_p somewhat, for example a 25%

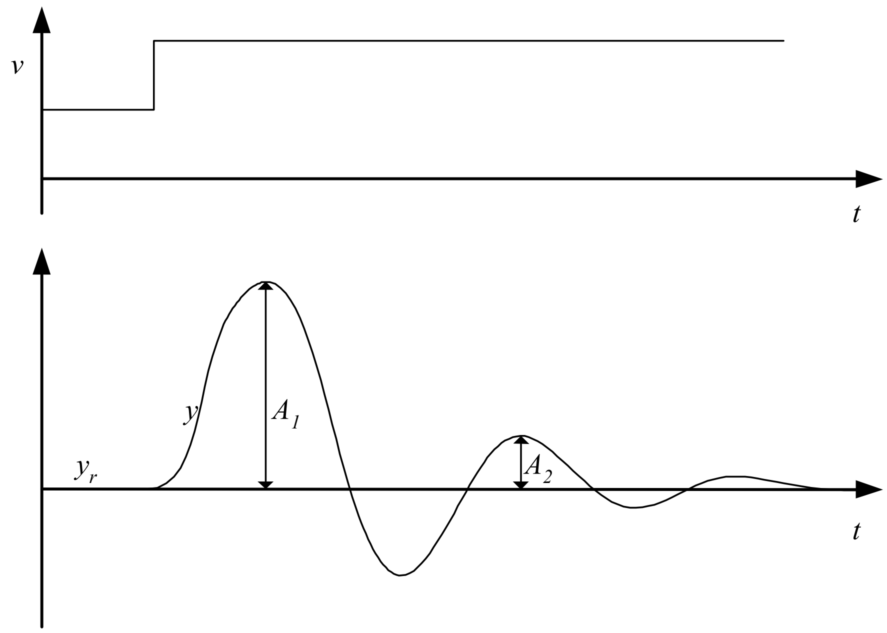

Figure 4.1: Good stability (according to Ziegler and Nichols)

decrease.

- Too good stability (which corresponds to sluggish control): Increase K_p somewhat, for example a 25% increase.

4.3 The P-I-D method

The P-I-D method is a simple and intuitive method (which does not require the control system to have sustained oscillations, as in the Ziegler-Nichols' closed loop method, cf. Section 4.4). The method is based on experiments on the established control system (or on a simulator of the control system), see Figure 4.2. The method is as follows:

1. Bring the process to or close to the normal or specified operation point by adjusting the nominal control signal u_0 (with the controller in manual mode).

2. Controller tuning:

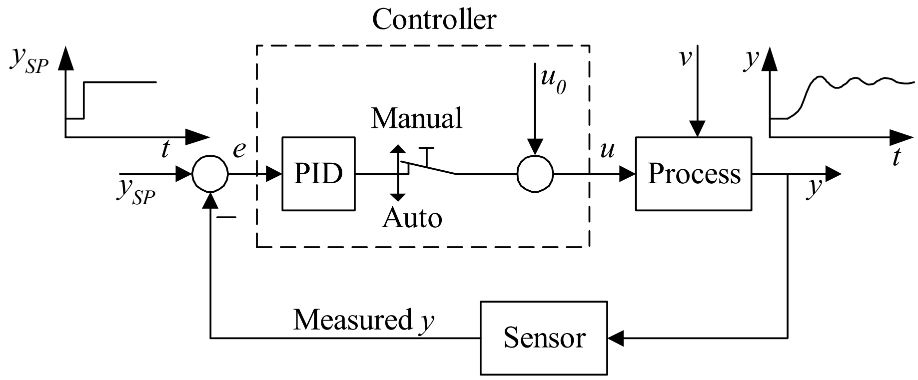

Figure 4.2: The P-I-D method is applied to the established control system.

- **P controller**: Ensure that the controller is a P controller with $K_p = 0$ (set $T_i = \infty$ and $T_d = 0$). Increase K_p until the control loop gets satisfactory stability as seen in the response in the measurement signal after e.g. a step in the setpoint or in the disturbance (exciting with a step in the disturbance may be impossible on a real system, but it possible in a simulator).

  If you do not want to start with $K_p = 0$, you can try $K_p = 1$ (which is a good initial guess in many cases) and then increase or decrease the K_p value until you are content with the stability of the control loop.

- **PI controller**:

  (a) Start by executing the procedure for a P controller (see above).

  (b) Activate the integral term by reducing T_i until the loop gets a little too poor stability. Alternatively, you can jump to the following T_i-value: $T_i = T_p/1.5$, where T_p is the time period of the damped oscillations when using the P controller. Because of the introduction of the I-term, the loop will have a somewhat reduced stability than with the P controller only.

  (c) Adjust K_p (you can try decreasing K_p by 20%) until the stability of the loop is satisfactory.

- **PID controller**:

  (a) Start by executing the procedure for a P controller (see above).

  (b) Then activate both the integral term by reducing T_i – an initial guess is $T_i = T_p/2$ where T_p is the time period of the damped oscillations for the P controller, and the derivative term by increasing T_d – an initial guess is $T_i/4$.

(c) Adjust K_p (you can try increasing it by 20%) until the stability of the loop is satisfactory.

Example 4.1 ***Controller tuning of a wood-chip level control system with the P-I-D method***

I have used the P-I-D method on the simulator shown in Figure 2.15. The PID parameter values became

$$K_p = 2.1;\, T_i = 10\text{min} = 600s;\, T_d = 2.5\text{min} = 150\text{s} \tag{4.5}$$

Figure 4.3 shows the resulting responses. The control system seems to have satisfactory stability.

Figure 4.3: Example 4.1: Level control of the wood-chip tank with a P-controller. (The front panel of the simulator is as shown in Figure 2.15.)

[End of Example 4.1]

4.4 Ziegler-Nichols' closed loop method

Ziegler and Nichols published in 1942 a paper [20] where they described two methods for tuning the parameters of P-, PI- and PID controllers. These two methods are the *Ziegler-Nichols' closed loop method* (which is described in this section) and the *Ziegler-Nichols' open loop method* (described in Section 4.6). These methods are still useful despite many years of research on PID tuning, and they form the basis of some auto-tuning methods (auto-tuning is described in Section 4.8).

The method is based on experiments executed on an established control loop (a real system or a simulated system), see Figure 4.4.

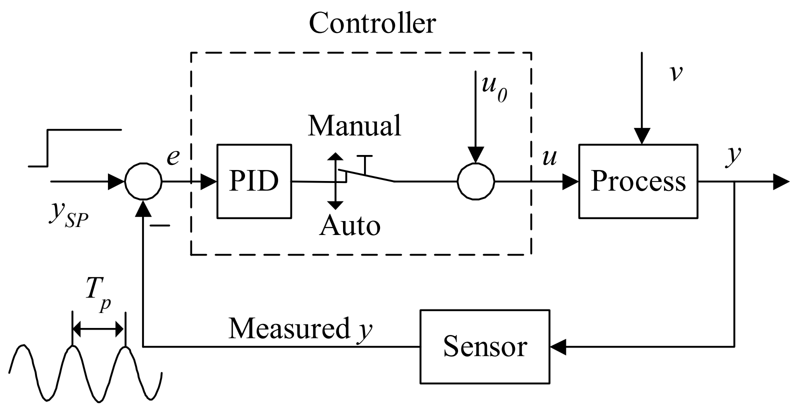

Figure 4.4: The Ziegler-Nichols' closed loop method is executed on an established control system.

The tuning procedure is as follows:

1. Bring the process to (or as close to as possible) the specified *operating point* of the control system to ensure that the controller during the tuning is "feeling" representative process dynamic[1] and to minimize the chance that variables during the tuning reach limits. You can bring the process to the operating point by manually adjusting the control variable, with the controller in manual mode, until the process variable is approximately equal to the setpoint.
2. Turn the PID controller into a *P controller* with gain $K_p = 0$ (set $T_i = \infty$ and $T_d = 0$). Close the control loop by setting the controller

[1] This may be important for nonlinear processes.

in automatic mode.

3. Increase K_p until there are *sustained oscillations* in the signals in the control system, e.g. in the process measurement, after an excitation of the system. (The sustained oscillations corresponds to the system being on the stability limit.) This K_p value is denoted the *ultimate (or critical) gain*, K_{p_u}.

   The excitation can be a step in the setpoint. This step must be small, for example 5% of the maximum setpoint range, so that the process is not driven too far away from the operating point where the dynamic properties of the process may be different. On the other hand, the step must not be too small, or it may be difficult to observe the oscillations due to the inevitable measurement noise.

   It is important that K_{p_u} is found without the actuator being driven into any saturation limit (maximum or minimum value) during the oscillations. If such limits are reached, you will find that there will be sustained oscillations for any (large) value of K_p, e.g. 1000000, and the resulting K_p-value (as calculated from the Ziegler-Nichols' formulas, cf. Table 4.1) is useless (the control system will probably be unstable). One way to say this is that K_{p_u} must be the smallest K_p value that drives the control loop into sustained oscillations.

4. Measure the *ultimate (or critical) period* T_u of the sustained oscillations.

5. *Calculate the controller parameter values* according to Table 4.1, and use these parameter values in the controller.

   The lowpass filter time constant T_f (cf. Section 2.6.7) can be set to

   $$T_f = 0.1T_d \tag{4.6}$$

   (if no other specification exists).

   If the stability of the control loop is poor, try to improve the stability by decreasing K_p.

	K_p	T_i	T_d
P controller	$0.5K_{p_u}$	∞	0
PI controller	$0.45K_{p_u}$	$\frac{T_u}{1.2}$	0
PID controller	$0.6K_{p_u}$	$\frac{T_u}{2}$	$\frac{T_u}{8} = \frac{T_i}{4}$

Table 4.1: Formulas for the controller parameters in the Ziegler-Nichols' closed loop method.

Example 4.2 ***The Ziegler-Nichols' closed loop method***

Figure 4.5 shows the signals in the simulated wood-chip level control system shown in Figure 2.15 (page 32). The system was excited by a step in the setpoint from 10m to 10.5m. The ultimate gain was $K_{p_u} = 3.1$, and

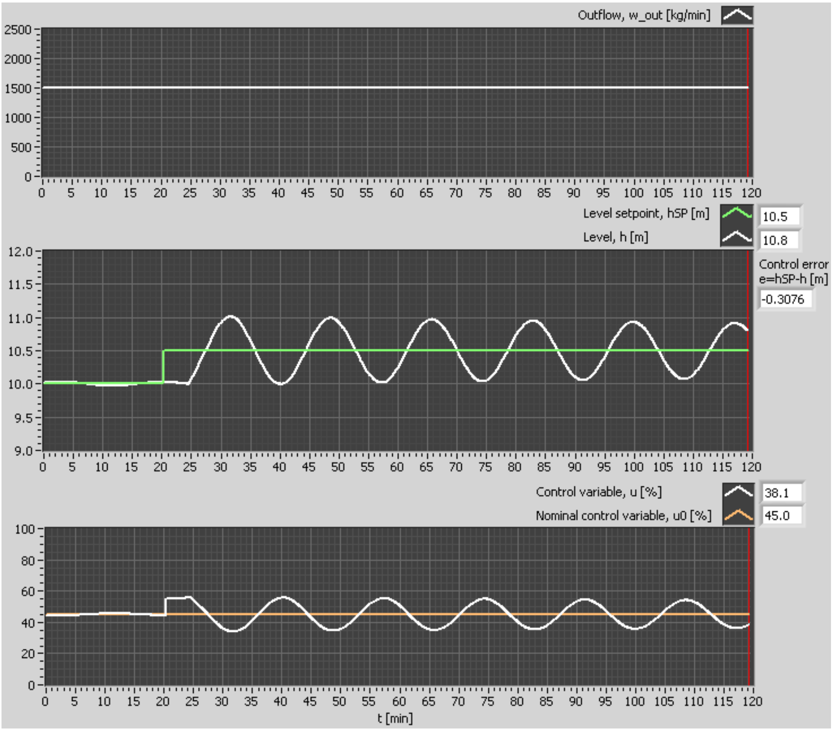

Figure 4.5: Example 4.2: The tuning phase of the Ziegler-Nichols' closed-loop method. (The front panel of the simulator is as shown in Figure 2.15.)

the ultimate period is approximately $T_u = 18$min. From Table 4.1 we get the following PID parameters:

$$K_p = 1.86;\ T_i = 9\text{min} = 540\text{s};\ T_d = 2.25\text{min} = 135\text{s} \tag{4.7}$$

Figure 4.6 shows signals of the control system with the above PID parameter values. The control system has satisfactory stability. The amplitude ratio in the damped oscillations is less than 1/4, that is, which means that the stability is a little better than prescribed by Ziegler and Nichols'.

[End of Example 4.2]

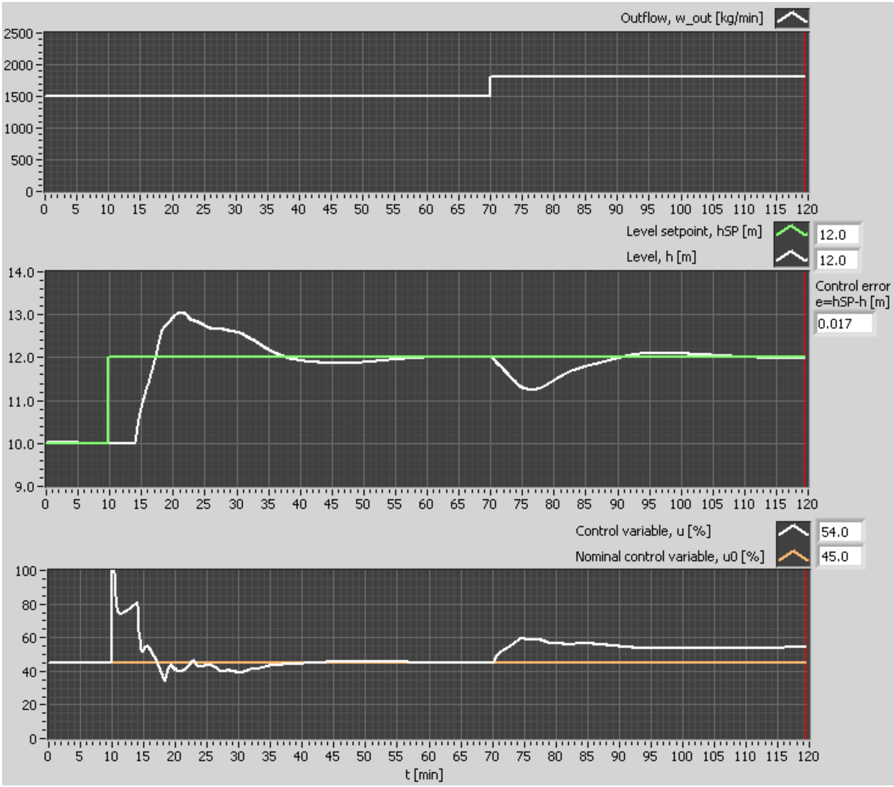

Figure 4.6: Example 4.2: Time responses with PID parameters tuned using the Ziegler-Nichols' closed loop method

Some comments to the Ziegler-Nichols' closed loop method

1. *You do not know in advance the amplitude of the sustained oscillations.* The amplitude depends partly of the initial value of the process measurement. By using the Åstrøm-Hägglund's tuning method described in Section 4.5 in stead of the Ziegler-Nichols' closed loop method, you have full control over the amplitude, which is beneficial, of course.

2. *For sluggish processes it may be time consuming* to find the ultimate gain in physical experiments. The Åstrøm-Hägglund's method reduces this problem since the oscillations come automatically.

3. If the operating point varies and if the process dynamic properties depends on the operating point, you should consider using some kind of *adaptive control or gain scheduling*, where the PID parameter are adjusted as functions of the operating point.

If the controller parameters shall have fixed value, they should be tuned in the worst case as stability is regarded. This ensures proper stability if the operation point varies. The worst operating point is the operation point where the process gain has its greatest value and/or the time delay has its greatest value.

4. *The responses in the control system may become unsatisfactory* with the Ziegler-Nichols' method. 1/4 decay ratio may be too much, that is, the damping in the loop is too small. A simple re-tuning in this case is to reduce the K_p somewhat, for example by 20%.

   A possibly better way to re-tune the controller for better stability is described by Ziegler and Nichols in [20]. They suggested to decrease K_p, $1/Ti$ and T_d with the same factor, for example 10%.[2]

In the beginning

The Ziegler and Nichols' methods have definitely proven to be useful, but they actually met some resistance in the beginning. In [2] Ziegler reports from a meeting in the American Society of Mechanical Engineers (ASME): "*The questions at the end were pretty bitter because they (the 'old-timers') could not stomach this ultimate sensitivity*[3]*. The questions got worse and worse and I was answering them. Finally a little guy in the back of the room got up. He was from Goodyear. Since he was on the committee he had received an advance copy of the paper. He stuttered some, and stammered out for all to hear: 'We had one process in our plant, a very bad one, and so I tried this method and it just worked perfectly.' That broke up the meeting.*"

4.5 Åstrøm-Hägglund's On/off method

Åstrøm-Hägglund's On/off method can be regarded as a practical implementation of the Ziegler-Nichols' closed loop method described in Chapter 4.4. There are a few practical problems with the Ziegler-Nichols' method:

- It may be time-consuming to find the least controller gain K_p which gives sustained oscillations.

[2]Note: Decreasing $1/Ti$ is the same as increasing T_i.

[3]which implies that the control system is on the stability limit and *oscillates*