Foreword

Automated process control offers so many advantages over manual control that the majority of today’s industrial processes use it at least to some extent. Breweries, wastewater treatment plants, mining facilities, the automotive industry, and just about every other industry sector use it.

Maintaining process variables such as pressure, flow, level, temperature, and pH within a desired operating range is of the utmost importance to manufacturing products with a predictable composition and quality.

The Instrumentation and Process Control Training System, series 3530, is a state-of-the-art system that faithfully reproduces an industrial environment in which students can develop their skills in the installation and operation of equipment used in the process control field. The use of modern industrial-grade equipment is instrumental in teaching the theoretical and the hands-on knowledge that is required to work in the process control industry.

The modularity of the system allows the instructor to select the equipment required to meet the objectives of a specific course. Two versatile, mobile workstations on which all the equipment is installed are the basis of the system. Several optional components used in pressure, flow, level, temperature and pH control loops are available as well as various valves, calibration equipment, controllers and software.

We hope that your learning experience with the Instrumentation and Process Control Training System will be the first step toward a successful career in the process control industry.
Table of Contents

Unit 1  Process Characteristics ................................................................. 1

Ex. 1-1 Determining the Dynamic Characteristics of a Process .......................................................... 15

Unit 2  Feedback Control ........................................................................... 31

Ex. 2-1 Tuning and Control of a Pressure Loop ................................. 51
Recapitulation of relevant control schemes. Tuning with the trial-and-error method.

Ex. 2-2 Tuning and Control of a Flow Loop ................................. 63
Brief review of new control modes. Tuning with the ultimate-cycle method. Limits of the ultimate-cycle method.

Ex. 2-3 Tuning and Control of a Level Loop ................................. 75
The open-loop Ziegler-Nichols method.

Ex. 2-4 Cascade Control of a Level/Flow Process ................................. 85
Cascade control. Tuning a cascade control system.

Unit 3  Troubleshooting a Process Control System ................................. 101
Troubleshooting. Plant shutdown.

Ex. 3-1 Guided Process Control Troubleshooting ................................ 107
Setting the scene.

Ex. 3-2 Non-Guided Process Control Troubleshooting ............... 115
Non-guided troubleshooting.

Appendix A  I.S.A. Standard and Instrument Symbols ............................... 117

Index .................................................................................................................. 129
Bibliography ....................................................................................................... 131
We Value Your Opinion! ................................................................................................................................. 133
Sample Exercise
Extracted from
Student Manual
Tuning and Control of a Pressure Loop

**EXERCISE OBJECTIVE**
Familiarize yourself with the use and manual tuning of P, PI, and on-off control schemes applied to pressure loops.

**DISCUSSION OUTLINE**
The Discussion of this exercise covers the following points:
- Recapitulation of relevant control schemes
- Tuning with the trial-and-error method

**DISCUSSION**
This exercise introduces three control schemes and puts them to use in a pressure process loop. This allows a comparative analysis of the different schemes in terms of efficiency, simplicity, and applicability to various situations. An intuitive method to tune controllers is also presented.

**Recapitulation of relevant control schemes**
A controller in proportional mode (P mode) outputs a signal \( m(t) \) – manipulated variable which is proportional to the difference between the target value (SP: set point) and the actual value of the variable \( c(t) \) – controlled variable. This simple scheme works well but typically causes an offset. The only parameter to tune is the controller gain \( K_c \) (or the proportional band \( PB\% = 100\%/K_c \) if your controller uses this parameter instead).

A controller in proportional/integral mode (PI mode) works in a fashion similar to a controller in P mode, but also integrates the error over time to reduce the residual error to zero. The integral action tends to respond slowly to a change in error for large values of the integral time \( T_i \) and increases the risks of overshoot and instability for small values of \( T_i \). Thus, the two parameters which require tuning for this control method are \( K_c \) (or \( PB\% \)) and \( T_i \) (or the integral gain, defined as \( G_i = 1/T_i \)).

The On-off control mode is the simplest control scheme available. It involves either a 0% or a 100% output signal from the controller based on the sign of the measured error. The option to add a dead band is available with most controllers to reduce the oscillation frequency and prevent premature wear of the final control element. There are no parameters to specify for this mode beyond a set point and dead band parameters. Note that it is possible to simulate an On-off mode with a controller in P mode for a large value of \( K_c \) (or a very small \( PB\% \)).

**Tuning with the trial-and-error method**
The trial and error method of controller tuning is a procedure to adjust the P, I, and D parameters until the controller is able to rapidly correct its output in
response to a step change in the error. This correction is to be performed without excessive overshooting of the controlled variable.

This method is widely used because it does not require the characteristics of the process to be known and it is not required bringing the process into a sustained oscillation. Another important aspect of this method is that it is instrumental in developing an intuition for the effects of each of the tuning parameters.

However, the trial and error method can be daunting to perform for inexperienced technicians because a change in tuning constant tends to affect the action of all three controller terms. For example, increasing the integral action will increase the overshooting, which in turn will increase the rate of change of the error, which will then increase the derivative action. A structured approach and experience help in obtaining a good tuning relatively quickly without resorting to involved calculations.

A good trial-and-error method is to follow a geometrical progression in the search for optimal parameters. For example, multiplying or dividing one of the tuning parameters by two at each iteration can help you converge quickly toward an optimal value of the parameter.

**A procedure for the trial-and-error method**

The trial-and-error method is performed using the following procedure (also refer to Figure 2-25 and Figure 2-26 for PI control):

1. Set the controller in the mode you want to use: P, PI, PD, or PID. Follow the instructions to adjust every parameter relevant to the mode you are using. Note that you can use the PID mode to perform any of the modes by simply setting the parameters to appropriate values (e.g. $T_d = 0$ for PI mode).

**Adjusting the P action**

2. With the controller in manual mode, turn off the integral and derivative actions of the controller by setting $T_i$ and $T_d$ respectively to the largest possible value and 0.

3. Set the controller gain $K_c$ to an arbitrary but small value, such as 1.

4. Place the controller in the automatic (closed-loop) mode.

5. Make a step change in the set point and observe the response of the controlled variable. The set point change should be typical of the expected use of the system.

Since the controller gain is low, the controlled variable will take a relatively long time to stabilize (i.e. the response is likely to be overdamped).

6. Increase $K_c$ by a factor of 2 and make another step change in the set point to see the effect on the response of the controlled variable.

The controller gain $K_c$ is related to the proportional band: $PB\% = 100%/K_c$.

If your controller uses the proportional band, start with a value of $PB\% = 100\%$ and replace instructions to increase $K_c$ by a factor of two by a decrease of $PB\%$ by a factor of two.
With the controller in manual mode, turn off the integral and derivative actions. Set the controller gain to 1.0.

Place the controller in automatic mode.

Make a step change in the set point.

Is the process response underdamped and oscillatory?

- No: Increase the controller gain to twice its value.
- Yes: Set the gain to halfway between the actual gain and the previous gain.

Bring in the integral action by setting the integral time at a high value.

Make a step change in the set point.

Is the process response underdamped and oscillatory?

- No: Decrease the integral time by a factor of 2.
- Yes: Set the integral time to halfway between the actual time and the previous time.

Bring in the derivative action by setting the derivative time at a low value.

Make a step change in the set point.

Is the process response longer and is overshooting amplified?

- No: Increase the derivative time to twice its value.
- Yes: Reduce the derivative time to obtain the fastest response without overshooting amplification.

Fine tune the controller to meet the response requirements.

Figure 2-25. Trial-and-error tuning method.
The objective is to find the value of $K_c$ at which the response becomes underdamped and oscillatory. This is the ultimate controller gain. Keep increasing $K_c$ by factors of 2, performing a set point change after each new attempt, until you observe the oscillatory response.

Once the ultimate controller gain is reached, revert back to the previous value of $K_c$ by decreasing the controller gain by a factor of 2. The P action is now set well enough to add another control action if required.

**Adjusting the I action**

7. Start bringing in integral action by setting the integral time $T_i$ at an arbitrarily high value. Decrease $T_i$ by factors of 2, making a set point change after each setting.

Do so until you reach a value of $T_i$ at which the response of the controlled variable becomes underdamped and oscillatory. At this point, revert back to the previous value of $T_i$ by increasing $T_i$ to twice its value.

The I action is now set and you can now proceed to the adjustment of the D action if required.

**Adjusting the D action**

8. Start bringing in derivative action by setting the derivative time at an arbitrarily low value. Increase $T_d$ by factors of 2, making a set point change after each setting.

Do so until you reach the value of $T_d$ that gives the fastest response without amplifying the overshooting or creating oscillation.

The D action is now set.

**Fine-tuning of the parameters**

9. Fine-tune the controller until the requirements regarding the response time and overshooting of the controlled variable are satisfied.

**A complementary approach to trial-and-error tuning**

Another, more visual approach is to use Figure 2-26 to assist you in tuning your controller. The figure presents responses of a PI process to a step change for different combinations of parameters. A good tuning is shown in the center of the figure for 'optimal' $K_c$ and $T_i$ parameters. The tuning in the center is not necessarily the most appropriate for the process you want to control, but the response shown is a good target for a rough first tuning.

The figure also shows responses for detuned parameters (both above and below the 'optimal' $K_c$ and $T_i$). Comparing the response you obtain for your system with the detuned responses in the figure tells you in which direction to change $K_c$, $T_i$, or both to converge towards the center case. Changing the parameters by a factor of two at every step until you get very close to the optimal value is a good method to converge rapidly.
Derivative action can then be added to the control scheme if required by following step 8 of the Trial-and-error method. Then, fine-tune the parameters to optimize the control and to meet the specific requirements of your process.

**Procedure Outline**

The Procedure is divided into the following sections:

- Set up and connections
- Adjusting the differential pressure transmitter
- Controlling the pressure loop
- Analyzing the results

**Procedure**

**Set up and connections**

1. Connect the equipment according to the piping and instrumentation diagram (P&ID) shown in Figure 2-27 and use Figure 2-28 to position the equipment correctly on the frame of the training system.
Table 2-2. Material to add to the basic setup for this exercise.

<table>
<thead>
<tr>
<th>Name</th>
<th>Model</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differential pressure transmitter (high-pressure range)</td>
<td>46920</td>
<td>PDIT 1</td>
</tr>
<tr>
<td>Solenoid valve</td>
<td>46951</td>
<td>S</td>
</tr>
<tr>
<td>Controller</td>
<td>*</td>
<td>PIC</td>
</tr>
<tr>
<td>Pressure control valve</td>
<td>46950-**</td>
<td>PCV</td>
</tr>
</tbody>
</table>

Figure 2-27. P&ID – Pressure control loop.
2. Connect the control valve to the pneumatic unit.

3. Connect the pneumatic unit to a dry-air source with an output pressure of at least 700 kPa (100 psi).

4. Wire the emergency push-button so that you can cut power in case of emergency.

5. Do not power up the instrumentation workstation yet. You should not turn the electrical panel on before your instructor has validated your setup—that is not before step 12.
6. Connect the solenoid valve so that a voltage of 24 V dc actuates the solenoid when you turn the power on at step 12.

7. Connect the controller to the control valve and to the differential pressure transmitter. You must also include the recorder in your connections. On channel 1 of the recorder, plot the output signal from the controller and on channel 2, plot the signal from the transmitter. Be sure to use the analog input of your controller to connect the differential pressure transmitter.

8. Figure 2-29 shows how to connect the different devices together.

9. Before proceeding further, complete the following checklist to make sure you have set up the system properly. The points on this checklist are crucial elements to the proper completion of this exercise. This checklist is not exhaustive, so be sure to follow the instructions in the *Familiarization with the Instrumentation and Process Control Training System* manual as well.

- All unused male adapters on the column are capped and the flange is properly tightened.
- The solenoid valve under the column is wired so that the valve opens when the system is turned on.
- The ball valves are in the positions shown in the P&ID.
- The three-way valve at the suction of the pump (HV1) is set so that the flow is directed toward the pump inlet.
- The control valve is fully open.
The pneumatic connections are correct.

The controller is properly connected to the differential pressure transmitter and to the control valve.

The paperless recorder is connected correctly to plot the appropriate signals on channel 1 and channel 2.

10. Ask your instructor to check and approve your setup.

11. Remove one of the caps from the top of the column. This maintains the pressure in the column at the atmospheric pressure.

12. Power up the electrical unit, this starts all electrical devices as well as the pneumatic unit. Activate the control valve of the pneumatic unit to power the devices requiring compressed air.

13. In manual mode, set the output of the controller to 0%. The control valve should be fully open. If it is not, revise the electrical and pneumatic connections and make sure the calibration of the I/P converter is appropriate.

14. Test your system for leaks. Use the drive to make the pump run at low speed to produce a small flow rate. Gradually increase the flow rate, up to 50% of the maximum flow rate that the pumping unit can deliver (i.e., set the drive speed to 30 Hz). Repair any leaks and stop the pump.

Adjusting the differential pressure transmitter

Be sure to use the differential pressure transmitter, Model 46920. This differential pressure transmitter has a high-pressure range.

15. Make sure the impulse line of the differential pressure transmitter is free of water and that it is connected to the pressure port at the top of the column.

16. Configure the differential pressure transmitter so that it gives pressure readings in the desired units. Set transmitter parameters so that it sends a 4 mA signal if the pressure is 0 kPa (0 psi) and a 20 mA signal if the pressure is 32 kPa (4.6 psi).

17. Adjust the zero of the differential pressure transmitter. The column is at atmospheric pressure because of the removed cap; therefore the transmitter will read 0 kPa (0 psi) when the pressure inside the column is equal to the atmospheric pressure.
18. Replace the column cap removed at step 11. This will allow pressure to build in the column when you turn the pump on.

Controlling the pressure loop

19. Set the pump to 40.0 Hz and wait for the pressure reading to stabilize. Valve HV5 and the solenoid valve must be open.

P mode

20. Program the controller to operate in P mode. Tune the controller according to the trial-and-error method presented above. Note the value of $K_c$:

$$K_c =$$

21. Record the response of the process to a step change in the set point of the controller from 40% to 60%. Transfer the data from the paperless recorder to a computer for later analysis.

PI mode

22. Program the controller to operate in PI mode. Tune the controller according to the trial-and-error method presented above. Note the value of $K_c$ and $T_i$:

$$K_c =$$

$$T_i =$$

23. Record the response of the process to a step change in the set point of the controller from 40% to 60%. Transfer the data from the paperless recorder to a computer for later analysis.

On-off mode

24. Program the controller to operate in On-off mode if such a mode is available with your controller. Experiment with different values of the dead band to visualize its effects. What do you observe as the dead band increases?

Set the dead band to a value well suited to the process and which avoids excessive load on the control valve.

If your controller does not have an On-off mode, simply set your controller in P mode with the largest possible $K_c$. The dead band typically cannot be adjusted in such cases.
25. Record the response of the process to a step change in the set point of the controller from 40% to 60%. Transfer the data from the paperless recorder to a computer for later analysis.

26. Stop the system.

Analyzing the results

27. Plot the response of the process for each mode using spreadsheet software. Compare the efficiency of the three modes and discuss their characteristics:

CONCLUSION

In this exercise, you learned to control a pressure loop using three different control modes: P, PI, and On-off. You experimented with the trial-and-error method of tuning a controller and developed a feel for the behavior of the control schemes for various values of the control parameters. The next exercise will cover a different method of optimizing a PID controller and will allow you to test your control skills on a flow process.

REVIEW QUESTIONS

1. What is the advantage of adding integral action to a proportional control scheme?

2. Why is On-off control not efficient in the experiment presented above?
3. Why does the trial-and-error method proceed with a factor of two change at every iteration?

4. What happens if you increase the $K_c$ parameter in a PI control scheme?

5. What happens if you decrease the $T_i$ parameter in a PI control scheme?
Sample

Extracted from

Instructor Guide
Exercise 2-1 Tuning and Control of a Pressure Loop

The loop will react differently depending if the solenoid valve is connected or not. The solenoid valve can also be used to test the troubleshooting skills of the students.

20. The PID parameters are dependent on your specific setup and cannot be expected to be adequate in every situation. The values given are indicative only and they were obtained with a Honeywell controller, Model 46961.

\[ K_c = 4.5 \text{ (PD mode, with } T_D = 0). \]

22. \( K_c = 3, \ T_i = 0.75, \text{ and } T_D = 0 \text{ (PID A mode)} \)

24. The frequency of oscillation of the controlled variable decreases while the amplitude of oscillation increases.

27. P Mode

![Pressure loop response – P mode.](image)

This mode responds quickly to the step change and stabilizes quickly to a new equilibrium value.
Exercise 2-1 Tuning and Control of a Pressure Loop

**PI - Mode**

Pressure loop response – PI mode.

The integral action eliminates the offset efficiently but adds some oscillation to the process response. The time required to settle to the set-point value is longer than in P mode because of the oscillations.

**On-Off Mode**

Pressure loop response – On-off mode.

The on-off mode produces a sinusoidal response following the set point closely. The amplitude of oscillation remains large even for tight dead band settings due to the fast evolving pressure of the process. The results look the same for a “simulated” on-off mode obtained with a high-gain P mode control scheme.

Discussing the efficiency of each control mode is not straightforward as the choice of a particular mode depends on the specific requirements of the application at hand. Nonetheless, the PI mode is usually considered to be more efficient as it converges rapidly to the set point value without offsets or sustained oscillations.
Exercise 2-1  Tuning and Control of a Pressure Loop

ANSWERS TO REVIEW QUESTIONS

1. A well tuned integral action eliminates the offset typical of P-only control.

2. On-off control works well for slow-changing processes with large capacitance. In the experiment at hand, the pressure in the tank varies too quickly to be controlled by a two-state scheme.

3. This method (geometrical progression) typically converges towards the solution faster than a fixed increment method (arithmetic progression).

4. The response will have a larger amplitude of oscillation and will take more time to stabilize.

5. Same answer as question 4.
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