Closed-Loop Position Control, Proportional Mode

EXERCISE OBJECTIVE

- To describe the proportional control mode;
- To describe the advantages and disadvantages of proportional control;
- To define residual error, proportional gain, proportional band, and oscillation;
- To describe how the manual reset method can be used to eliminate the residual error.

DISCUSSION

Closed-Loop Control of Cylinder Rod Position

In the previous exercise, you controlled the position of a cylinder rod with an open-loop system. The position of the rod changed when the load varied because the system was controlling the valve operation and not the actual position of the cylinder rod.

The addition of a controller and a feedback loop to a position control system markedly reduces the variations in the rod position. This type of system, called closed-loop control system, is illustrated in Figure 4-1.

- The controller compares the setpoint (desired position) to the measured position and corrects for any difference between the two by modifying the setting of the valve until the system reaches a state of equilibrium.
- The feedback loop contains a position transducer that measures the actual rod position and generates a proportional signal which is sent back to the controller.

Essential Elements of a Controller

Any controller contains two essential parts: the error detector and the mode section.

- The error detector compares the setpoint to the measured position and produces an error signal equal to the difference between the two. Errors occur when, for example, the operator changes the setpoint intentionally or when the actuator load changes.
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- The mode section performs mathematical operations which act on the error signal. The type of operations performed depends on the selected control mode. The control modes are the proportional (P) mode, integral (I) mode, differential (D) mode, or a combination of these. The resulting controller output signal is applied to the servo control valve to change the valve setting and, therefore, the air pressure to the actuator.

**Negative and Positive Feedbacks**

Two types of feedback are possible in closed-loop control systems: positive feedback and negative feedback.

- Positive feedback increases the difference between the setpoint and measured position, as Figure 4-2 (a) shows. Positive feedback can result in violent and sustained oscillations within the system. For obvious reasons, positive feedback is not employed in closed-loop control.

- Negative feedback decreases the difference between the setpoint and measured variable (position) and acts to restore equilibrium, as Figure 4-2 (b) shows.

If, for example, the rod exceeds the position called for by the setpoint, negative feedback will decrease the control voltage of the valve and, therefore, the air pressure to the actuator, thus helping to restore the position. With positive feedback, however, the valve opening would be increased, making the situation worse.

Figure 4-1. Closed-loop control of cylinder rod position.
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Implementation of Negative Feedback

In the system of Figure 4-1, negative feedback is implemented in the error detector section of the controller. This entails applying the setpoint signal to a positive (+) input of the error detector, and the position transducer signal (feedback) to the negative (−) input of the error detector. In this manner, the error detector output is equal to the setpoint value minus the signal corresponding to the measured position, so that when the cylinder rod position changes, the error detector output and, therefore, the controller output change (negative feedback).

Proportional (P) Control Mode

As mentioned previously, the operation mode of the controller determines the type of mathematical operations performed on the error detector output signal in order to produce a change in the valve setting.
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The simplest control mode is the proportional (P) mode. Figure 4-3 shows the diagram of a controller operating in this mode:

- The error detector compares the feedback signal to the setpoint and produces an error signal $E_p$ equal to the difference between the two;
- The proportional amplifier amplifies the error signal by a factor $K_p$ to produce the controller output signal.

![Diagram of a controller operating in the proportional (P) mode.](image)

The controller output signal is proportional to the error signal at all times, hence the name proportional mode. The greater the error is, the greater the controller output will be. This relationship can be expressed mathematically:

$$C_o = K_p \times E_p$$

where  
\( C_o \) is the controller output;  
\( K_p \) is the proportional gain;  
\( E_p \) is the error.

The magnitude of the controller output signal is limited to the saturation levels of the proportional amplifier. If, for example, the saturation levels of this amplifier are +13.0 and -13.0 V, the controller output signal will never exceed these voltages. This means that once the controller output signal has reached one of the saturation levels, an increase in the error signal no longer produces an increase in controller output signal.

It is sometimes necessary to further limit the excursion of the controller output signal in order to adapt it to the input voltage range of a valve. This can be achieved by using a limiter circuit.

Figure 4-4, for example, shows the LIMITER circuit of the trainer PID Controller. This circuit limits the controller output signal to the levels set by its LOWER and UPPER LIMIT potentiometers. The LOWER LIMIT potentiometer sets the maximum level for negative controller voltages; it can be adjusted between 0 and about -13 V. The UPPER LIMIT potentiometer sets the maximum level for positive controller voltages; it can be adjusted between 0 and about 13 V.
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Advantages and Disadvantages of the Proportional Control Mode

The main advantage of the proportional control mode is the rapidity at which the controller responds to a change in error signal to return the system to equilibrium. For example, Figure 4-5 shows what happens in the proportional control mode when the setpoint is changed suddenly. One can observe that the error greatly increases when the setpoint is changed, but the controller reacts immediately to correct this error. Since there is no delay in the response of the controller, the error rapidly decreases until the system reaches a state of equilibrium.

As Figure 4-5 shows, once the system has reached the state of equilibrium, a residual error remains between the setpoint and measured variable. This is the main disadvantage of the proportional control mode. Reducing the error to zero would cause the controller output to be null. This would cause the valve input signal to be null and consequently the output pressure. Hence, a residual error is required to maintain the controller output at a desired value.

The higher the proportional gain $K_p$ is, the lower the residual error will be. However, increasing the gain will also increase the system tendency toward instability. Indeed, if the gain becomes too high, the system will start to oscillate without being able to return to the state of equilibrium. Thus, increasing the gain is not the ideal solution to eliminate the residual error.
Manual Reset

Manual reset consists in eliminating the residual error for one given load condition by adding a bias voltage (offset) to the proportional controller output signal. This is illustrated in Figure 4-6. For a given load condition, the bias voltage is adjusted manually until the feedback signal equals the setpoint. Because the bias voltage is adjusted manually, this method is often referred to as manual reset.

With manual reset, the equation of the proportional controller output becomes:

$$C_O = K_p \times E_p + \text{bias}$$

The advantage of the manual reset is that it eliminates the residual error without affecting the proportional gain. However, the error is eliminated only for one given load condition. For other load conditions requiring a different valve setting, a residual error will exist to maintain the required controller output. Therefore, manual reset is used in systems where the load remains fairly constant.
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Figure 4-6. Manual reset consists in adding a bias voltage to the proportional controller output signal.

Proportional Band

The proportional band is the range over which the error signal must change to cause the controller output signal to vary over its full range. The proportional band varies in inverse proportion to the proportional gain. In equation form:

\[ P_B = \frac{1}{K_P} \times 100\% \]

where \( P_B \) is the proportional band; 
\( K_P \) is the proportional gain.

The higher the proportional gain, the lower or “narrower” the proportional band will be and, therefore, the lower the error required to cause the controller output signal to change over its full range.

For example, Figure 4-7 shows the error-versus-controller output relationship for two different gains, \( K_{P1} \) and \( K_{P2} \), with \( K_{P1} \) being higher than \( K_{P2} \). As the figure shows, the narrower band corresponds to the higher gain, \( K_{P1} \).

You will note in Figure 4-7 that when the error is within the proportional band, the controller output signal is proportional to the error, and the gain determines the proportional relationship. If, however, the error exceeds the proportional band, the controller output signal saturates at either the lower or upper limit, depending on the polarity of the error.
Procedure summary

In the first part of the exercise, *Familiarization with the Components of a Proportional Controller*, you will familiarize yourself with the components and operation of a proportional controller.

In the second part of the exercise, *Proportional Control of Cylinder Rod Position*, you will study closed-loop control of cylinder rod positioning in the proportional control mode. You will determine the effect of increasing the controller proportional gain on the residual error. You will then use manual reset to eliminate the residual error.

**EQUIPMENT REQUIRED**

Refer to the Equipment Utilization Chart, in Appendix A of the manual, to obtain the list of equipment required to perform this exercise.
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PROCEDURE

Familiarization with the Components of a Proportional Controller

☐ 1. Connect the circuit shown in Figure 4-8. In this system, a proportional controller is built with the ERROR DETECTOR, the PROPORTIONAL AMPLIFIER, the SUMMING POINT, and the LIMITER of the PID Controller.

   Note: Do not connect the 0-10 V output of the [0-24 V] E/E converter to the negative input of the ERROR DETECTOR at this time. This will be done later in the exercise.

☐ 2. Make the following settings on the PID Controller:

   PROPORTIONAL (P) GAIN range ......................... LOW
   PROPORTIONAL (P) GAIN ................................. MIN.
   LOWER LIMIT ............................................ ½ of MAX.
   UPPER LIMIT ............................................. ½ of MAX.

☐ 3. Turn on the DC Power Supply and PID Controller.

☐ 4. On the PID Controller, select the SETPOINT potentiometer 1 and set the potentiometer to obtain 1.0 V at the SETPOINT output 1.

☐ 5. On the PID Controller, measure the DC error voltage at the ERROR DETECTOR output.

   With a setpoint voltage of 1.0 V at a positive input of the ERROR DETECTOR and without feedback voltage (0.0 V) at the negative input, the error voltage should be about 1.0 V (setpoint minus feedback voltage). Is this your observation?

   ☐ Yes  ☐ No
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Figure 4-8. Proportional (P) control of cylinder rod position.

6. On the PID Controller, measure the DC voltages at the input and output of the proportional amplifier and determine the voltage gain of the proportional amplifier for this gain setting. Record your result in Table 4-1.
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Table 4-1. Voltage gains of the proportional (P) amplifier for various gain settings.

<table>
<thead>
<tr>
<th>PROPORTIONAL GAIN RANGE</th>
<th>PROPORTIONAL GAIN SETTING</th>
<th>GAIN (MEASURED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW</td>
<td>MIN.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAX.</td>
<td></td>
</tr>
<tr>
<td>HIGH</td>
<td>MIN.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAX.</td>
<td></td>
</tr>
</tbody>
</table>

7. Set the PROPORTIONAL GAIN potentiometer to MAX. Determine the voltage gain of the proportional amplifier for this gain setting. Record your result in Table 4-1.

8. Pull out the knob of the PROPORTIONAL GAIN potentiometer to select the HIGH GAIN range, then set the PROPORTIONAL GAIN to MIN.

Determine the voltage gain of the proportional amplifier for this gain setting and record your result in Table 4-1.

9. While observing the proportional amplifier output voltage, slowly increase the PROPORTIONAL GAIN to MAX.

Observe that beyond a certain gain, the voltage ceases to increase because it has reached the positive saturation level of the proportional amplifier (about 13.5 V). Is this your observation?

   □ Yes    □ No

10. Using the SETPOINT potentiometer 1, decrease the proportional amplifier input voltage to 0.2 V. Then determine the voltage gain of the proportional amplifier with the PROPORTIONAL GAIN set to MAX. Record your result in Table 4-1.

When you have finished, leave the PROPORTIONAL GAIN range at HIGH and the PROPORTIONAL GAIN to MAX.

11. On the PID Controller, measure the DC voltage at the SUMMING POINT output. This voltage should approximately be equal to the proportional amplifier output voltage. Is this your observation?

   □ Yes    □ No
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- 12. On the PID Controller, measure the DC voltages at the input and output of the LIMITER. Observe that the output voltage is lower than the input voltage, due to the limiting action of the LIMITER.

- 13. While monitoring the LIMITER output voltage, slowly turn the knob of the UPPER LIMIT potentiometer clockwise. What happens to the voltage? Explain.

- 14. Set the SETPOINT potentiometer 1 to obtain -0.2 V at the proportional amplifier input.

  A negative voltage of approximately -10.0 V should now be present at the LIMITER input.

- 15. While monitoring the LIMITER output voltage, slowly turn the knob of the LOWER LIMIT potentiometer fully clockwise. What happens to the voltage? Why?

Proportional Control of Cylinder Rod Position

Preliminary settings

- 16. Set the PROPORTIONAL GAIN range at LOW and the PROPORTIONAL GAIN to MIN.

- 17. On the PID Controller, set the LOWER and UPPER LIMITS as follow:

  - Set the SETPOINT potentiometers 1 and 2 to obtain 10.0 V and 0.0 V, respectively, at the SETPOINT outputs 1 and 2. Then select the SETPOINT potentiometer 1;
  - Set the LOWER LIMIT potentiometer to MIN. This sets the lower limit at 0.0 V;
  - Increase the PROPORTIONAL GAIN until the LIMITER input voltage reaches about 12.0 V;
  - Set the UPPER LIMIT potentiometer to obtain 10.0 V at the LIMITER output.
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☐ 18. On the PID Controller, set the SETPOINT potentiometer 1 and the PROPORTIONAL GAIN as follow:
   - Set the SETPOINT potentiometer 1 to obtain 5.0 V at the SETPOINT output 1;
   - Set the PROPORTIONAL GAIN to obtain 5.0 V at the LIMITER input.

☐ 19. Verify the status of the trainer according to the procedure given in Appendix B.

☐ 20. On the Conditioning Unit, open the main shutoff valve and the required branch shutoff valves at the manifold.
   Set the main pressure regulator to obtain 630 kPa (90 psi) on the regulated pressure gauge.
   Set the pressure regulator PR2 to obtain 420 kPa (60 psi) on the pressure gauge PG2.

☐ 21. Place the system in the closed-loop mode. To do so, connect a lead between the 0-10 V output of the [0-24 V] E/E converter and the negative input of the ERROR DETECTOR.

☐ 22. Very slowly turn the knob of the PROPORTIONAL GAIN potentiometer clockwise until the cylinder rod extends about 2.5 cm (1 in).

☐ 23. Measure and record the feedback voltage generated by the [0-24 V] E/E converter at the negative input of the ERROR DETECTOR. This voltage is directly proportional to the rod position.
   Feedback voltage: _____ V

☐ 24. Measure the voltage at the ERROR DETECTOR output. This voltage corresponds to the error (difference) between the 5.0-V setpoint voltage and the feedback voltage. Is this your observation?
   ☐ Yes  ☐ No
25. While observing the ERROR DETECTOR output voltage, very slowly turn the potentiometer of the PROPORTIONAL GAIN clockwise.

You should observe that as the proportional gain is increased, the cylinder rod extends and consequently the error voltage decreases at the ERROR DETECTOR output.

Try to reduce the ERROR DETECTOR output voltage to 0.0 V by increasing the PROPORTIONAL GAIN. You should observe that beyond a certain gain, the system becomes unstable and starts to oscillate, because the gain is excessive. Record your observations.

Manual reset

26. Return the system to equilibrium by decreasing the PROPORTIONAL GAIN. Measure and record the error voltage for this proportional gain setting.

Error voltage: _____ V

27. Connect the SETPOINT output 2 to a positive input of the SUMMING POINT.

28. Slowly turn the knob of the SETPOINT potentiometer 2 clockwise until the ERROR DETECTOR output voltage becomes null.

   Note: Reduce the PROPORTIONAL GAIN if the system becomes unstable and starts to oscillate.

29. Measure the voltage present at the SETPOINT output 2. This is the bias voltage required to eliminate the error at the controller output.

   Bias: _____ V

30. Simulate a load increase by setting the Pressure Regulator PR2 to obtain 560 kPa (80 psi) on the Pressure Gauge PG2.

31. Is the error voltage at the ERROR DETECTOR output still null? Why?
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☐ 32. Do your observations confirm that the manual reset method is appropriate for eliminating the error in systems where the load varies?
   ☐ Yes    ☐ No

☐ 33. On the Conditioning Unit, close the shutoff valves, and turn the regulator adjusting knob completely counterclockwise.

☐ 34. Turn off the PID Controller and the DC Power Supply.

☐ 35. Disconnect and store all leads and components.

CONCLUSION

In this exercise, you studied closed-loop control of cylinder rod position with the simplest type of control mode: the proportional mode. In this mode, the controller output is equal to the proportional gain multiplied by the error. You saw that the proportional gain is inversely proportional to the proportional band.

The controller output is, at all times, proportional to the error as long as the error remains within the proportional band. If, however, the error exceeds the proportional band, the controller output will saturate.

The main disadvantage of the proportional control mode is that a residual error remains between the setpoint and measured variable at equilibrium. Increasing the controller gain reduces the residual error, but also increases the system tendency to instability. A method called manual reset allows elimination of the residual error by adding an offset voltage at the controller output. However, this method works for only one given load condition.

REVIEW QUESTIONS

1. What is the difference between positive and negative feedback?

   __________________________________________________________
   __________________________________________________________

2. What function does the error detector serve in a controller?

   __________________________________________________________
   __________________________________________________________
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3. Briefly describe the operation of a controller in the proportional mode.

__________________________________________________________________________

__________________________________________________________________________

4. What is the main disadvantage of the proportional control mode?

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__________________________________________________________________________

5. What does manual reset mean?

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6. What is the disadvantage of manual reset?

__________________________________________________________________________

__________________________________________________________________________

7. To increase the stability of the system response to a change in error signal, would you increase or decrease the proportional gain?

__________________________________________________________________________

__________________________________________________________________________