Control System Instrumentation

1. Introduction
2. Sensors, transmitters and transducers
3. Control valves
Introduction

- **Stirred tank heating system**
  - Measured liquid temperature with thermocouple
  - Transmit signal to controller
  - Perform control calculation
  - Send controller output to electrical heater

- **Process control system components**
  - Sensor – measures controlled output
  - Transmitter – transmits measurement signal
  - Controller – processes measurement signal
  - Final control element – imparts control action
Control System/Process Interface

M = Measurement  C = Controller  A = Actuator

Controller/process interface

Computer control system

Controller/process interface

Process
Sensors, Transmitter and Transducers

- **Sensor**
  - Produces a physical response related to the process variable
  - Thermocouple: temperature $\rightarrow$ millivolt signal

- **Transmitter**
  - Converts sensor signal to a signal appropriate for the controller
  - Temperature transmitter: millivolt signal $\rightarrow$ voltage signal

- **Transducer**
  - Converts signal from one form to another form
  - I/P converter: current signal $\rightarrow$ pneumatic signal

- **Standard ranges**
  - Analog: 4-20 milliamp, 1-5 volts
  - Pneumatic: 3-15 psig
Sensor Selection Criteria

1. Measurement range (span) – must cover anticipated range of measured variable
2. Performance – accuracy, repeatability, speed of response, etc.
3. Reliability – acceptable chance of failure
4. Materials of construction – compatible with application
5. Prior experience – new technologies require training
6. Safety – determine if failure has acceptable impact on process safety
7. Invasive or non-invasive – invasive probes inserted directly into process stream can foul
8. Cost – expense should be minimized and justified
Common Measurement Options

- Temperature
  » Thermocouple, resistance temperature detector (RTD)

- Flow
  » Orifice meter, venturi meter

- Pressure
  » Strain gauge, piezoelectric transducers

- Level
  » Pressure taps, float activated chain gauge

- Composition
  » Gas chromatography, mass spectrometry

- Some sensors measure multiple variables

- See Table 9.1 in text
Static and Dynamic Characteristics

- **Sensor gain**
  » 50 °C $\rightarrow$ 4 mA, 150 °C $\rightarrow$ 20 mA
  » Gain: 
    \[
    K_m = \frac{\text{output range}}{\text{span}}
    \]
  » Conversion:
    \[
    T_m(\text{mA}) = \frac{(20 - 4)\text{mA}}{(150 - 50) ^ \circ \text{C}} (T - 50) ^ \circ \text{C} + 4\text{mA} = \left(0.16 \frac{\text{mA}}{^ \circ \text{C}}\right)T(\text{C}) + 4\text{mA}
    \]

- **Sensor dynamics** – assume linear first order
  \[
  \frac{T_m(s)}{T(s)} = \frac{K_m}{\tau_m s + 1}
  \]
  » Good sensor: $\tau_m << \tau_p$ (process time constant)
Thermocouple Dynamics

- Energy balance on thermowell

\[ mC_p \frac{dT_m}{dt} = UA(T - T_m) \]

- Standard ODE form

\[
\frac{mC_p}{UA} \frac{dT_m}{dt} + T_m = T
\]

- Transfer function

\[
\frac{T_m'(s)}{T'(s)} = \frac{1}{mC_p s + 1} = \frac{1}{\tau_m s + 1}
\]

» Want to make \( \tau_m \) small
Measurement Accuracy

True value

Total error (maximum)

Systematic error (bias)

Random error (repeatability)

Most likely measured value

Number of occurrences of a particular reading

$g$, flow units
Control Valves

- Final control elements
  - Control system component that imparts the control action and allows the manipulated variable to be changed
  - The vast majority of final control elements are control valves that manipulate flows
Control Valve Properties

- **Failure mode**
  - Air-to-open (A-O): valve closes when instrument air is lost
  - Air-to-close (A-C): valve opens when instrument air is lost

- **Valve characteristic**
  - Linear – flow linear function of valve position
  - Quick opening – flow square root function of valve position
  - Equal percentage – derivative of flow proportional to valve position
  - Valve type chosen to make installed characteristic linear as possible (see text)
Control Valve Behavior

- Valve dynamics – assume linear first order

\[
\frac{U(s)}{P(s)} = \frac{K_v}{\tau_v s + 1}
\]

» Good valve: \( \tau_v \ll \tau_p \) (process time constant)

- Nonideal behavior

» Hysteresis – different flows obtained when value opening and closing at same valve position

» Deadband – no change in flow over a range of value positions

» Can be mostly overcome with valve positioners
Sizing Control Valves

- **Design equation**

\[ q = C_v f(l) \sqrt{\Delta P_v / g_s} \]
- \( q \) = flow rate
- \( C_v \) = valve coefficient
- \( l \) = lift (amount open)
- \( f(l) \) = valve characteristic
- \( \Delta P_v \) = pressure drop across valve
- \( g_s \) = specific gravity of fluid

- **Valve characteristic**

  - Linear: \( f = l \)
  - Quick opening: \( f = \sqrt{l} \)
  - Equal percentage: \( f = R^{l-1} \)
Control Valve Sizing Example

- Design a linear control valve that is 50% open at the nominal flow rate for a fluid with $g_s = 1$
- Pressure drop across valve: $\Delta p_v = 10$ psi
- Valve coefficient

$$C_v = \frac{q}{f(l) \sqrt{\Delta P_v / g_s}} = \frac{200}{0.5 \sqrt{10/1}} = 127$$