Instrumentation Technology
INST-1010
Introduction to Process Control

Basile Panoutsopoulos, Ph.D.
CCRI
Department of Engineering and Technology

Today's meeting

- Call Attendance
- Announcements
- Collect Homework
- Give examination
  - Display time clock
- Collect examinations
- Previous examination
  - Return
  - Discussion
- Introduce topic
  - Provide Handouts
  - Socratic discussion
  - Practice - Problems

Themes

- List the classifications of industrial control systems
- Describe the differences among industrial control systems
- Provide examples of each type
- Define common terms associated with industrial control systems

Themes

- Describe the differences between
  - open- and
  - closed-loop systems
- Define common terms associated with
  - open- and
  - closed-loop systems
- List the factors that affect the dynamic response of a closed-loop system
- Describe the operation of feed-forward control

Themes

- List three factors that cause the controlled variable to differ from the set-point

Themes

- Process Control
- Variables
- Automation
- Control Elements
- Control Loops
- Common Control Strategies
- Instrumentation
- Instrumentation and Industry
- Training
- Industry and Standards Organizations

HISTORICAL INTRODUCTION

Historical Introduction

- Industrial revolution (England) 1700s
- US surpasses England as the manufacturing leader
- 1900s the electric motor replaces steam engine and water wheels.

Historical Introduction

- Machines are manually operated.
- Between World War I and World War II the Feedback Control System is developed.
- Manually operation is replaced by automatic operation
- The term Industrial control is used to describe this type of system.
- During World War II significant advantages occurs in developing theory and practice of Automatic Control Systems.
- This technology was transferred to commercial applications.

Historical Introduction

- Today's technicians:
  - Install
  - Troubleshoot
  - Maintain
  - Repair
- The today's technicians must be highly trained.

INDUSTRIAL CONTROL SYSTEMS

Process Operation

- Instrumentation
  - Measure and control variables in industrial processes
    - Example: Process variables measured include pressure, flow, temperature, level, ph, humidity
- Process
  - Series of actions directed to same end
    - Manufacturing methods are processes
      - Mixing ingredients, assembling parts/systems, fabricating IC's, ….
- System Loop
  - Total Process: series of individual loops
  - Composite of each part that makes up complex process
- Process Loop
  - Individual loop that makes up system loop
  - Often just referred to as a loop

The Purpose of Measurement

- Four main purposes:
  - Continuous input to controller
  - Monitoring of process variables or equipment
  - Recording of information for trend indication or archive
  - Spot-checking of a process variable
- Systems may be complex
  - Many processes and variables being monitored at same time

Measurement Requirements

- Accuracy and reliability of measurements depend on process requirements
- Power plant/ Furniture kiln example
- Criticality of variables depends on process
  - Fast response for quickly changing variables
    - pressure or flow
  - Slower response for slower variables
    - Temperature or level

Errors in Measurement Systems

- Sources of error
  - Incorrect calibration
  - Noise
  - Speed of response
  - System degradation
  - Errors of observation
  - Transducer accuracy

Measuring Data

- Variables often measured
  - Temperature, flow, pressure, force, level, composition, density, color, resistance, ph, …..
  - Examples

Controlling Variables Automatically

- Adjustment to process based on measurement
- Examples
  - Sheet metal
  - Liquid level

Error Signal Evaluation/Feedback

- Error
  - Difference between set point and measurement
- Signal evaluation
  - Based on data measured, controller reacts accordingly
    - No action, increase, decrease
- Feedback
  - Based on measured value, corrective signal sent to controller
    - Speed of response depends on application

Open/Closed Loop Systems

- Open Loop
  - No feedback
- Closed Loop
  - Uses feedback for continuous correction

Noise

- Noise
  - Any signal other than the desired signal
  - Many sources
  - Noise gets added to signal
  - Large snr (Signal to Noise Ratio) desired

Kinds of Signals

- Signal:
  - Electrical
    - Analog - continuous range of values
    - Digital – discrete values, 1/0, on/off, true/false
  - Pneumatic
    - Air pressure

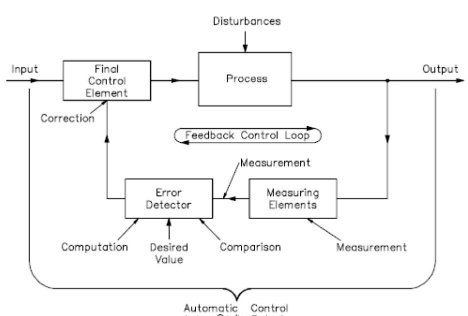
Kinds of Displays

- Audible
  - Tones, beeps, bells, etc.
- Visual
  - Pointer
    - Edgewise, circular
    - Scale typically graduated
      - Linear, nonlinear, logarithmic
  - Digital displays
    - Direct reading of variable
    - Rapidly replacing many pointer scale displays
  - Monitors
    - Text, graphics, color used to define process, variables, …

Remote versus Local Display

- Local
  - Variable measured and displayed at source
- Remote
  - Variable measured at source displayed remotely through a separate transmitter

Functions and Elements in an Automatic Control System



Process Control

- The regulation of system behavior by monitoring measured data from one or more sensors.

The need for a Control System

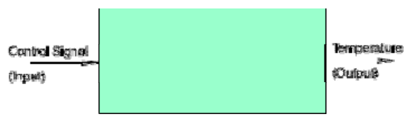
- Do we need to control a system at all?
- Let us consider the following situations:
  - What good is an airplane if you are a pilot and you can't make it go where you want it to go?
  - What good is a chemical products production line if you can't control temperature, pressure and pH in the process and you end up making tons of garbage?
  - What good is an oven if you can't control the temperature?
  - What good is a heat-treating department that is used to harden metal parts if you can't control the temperature?
  - What good is a pump if you can't control the flow rate it produces? (And, there are many times when the flow rate must be controlled.)

The need for a Control System

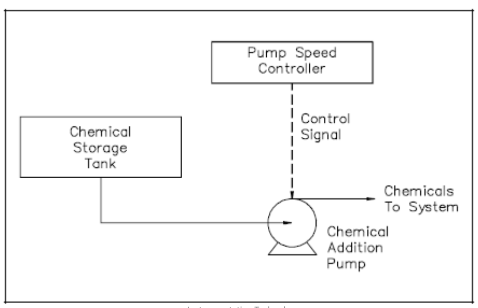
- The common denominator in all of these questions is that there is some physical quantity that must be somehow controlled in a way that ensures that the physical quantity takes on a value or, more practically, in a range between two values, that is specified.
- There are even times when the physical quantity should take on some pre-determined values that follow a function of time.
  - Example of that would be landing an airplane where you want the plane to meet the ground following a specified curve.
- We need to think about how to control physical quantities in general, and to determine what can be done - in a general way - to implement any scheme we devise.

Typical control system

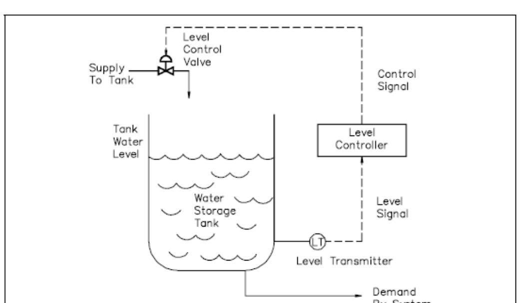
- Control system
- Control system input(s)
- Control system output(s)



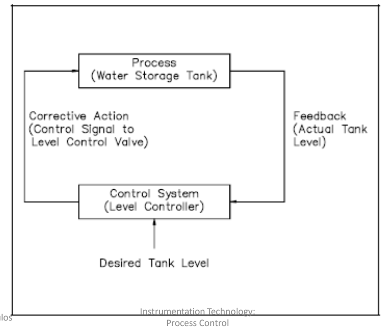
Typical Control Loops
Open Loop Control System



Typical Control Loops
Closed Loop Control System

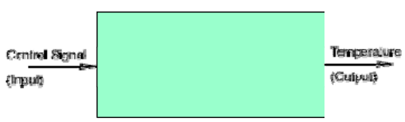


Closed Loop Control System Feedback



Typical Automatic Control System

- Automatic control system
- Manipulated variable(s) - Controlled system input(s)
- Controlled variable(s) - Control system output(s)

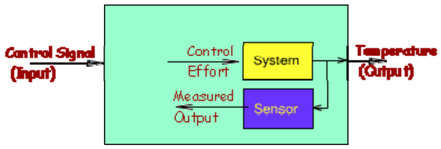


Typical Automatic Control System

- Automatic control system:
  - An ***automatic control system*** is a preset closed-loop control system that requires no operator action.
- Manipulated variable(s) - Controlled system input(s)
  - A ***manipulated variable*** is the process variable that is acted on by the control system to maintain the controlled variable at the specified value or within the specified range.
- Controlled variable(s) - Control system output(s)
  - A ***controlled variable*** is the process variable that is maintained at a specified value or within a specified range.

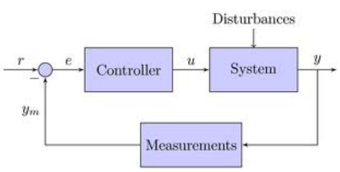
Typical control system

- Control system
- Control system input(s)
- Control system output(s)



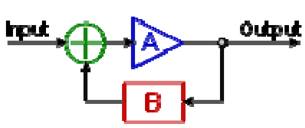
Typical control system

- Control system
- Control system input(s)
- Control system output(s)



Typical control system

- Control system
- Control system input(s)
- Control system output(s)



Automatic Process Control
Functions of an Automatic Control System

- Four essential functions
  - Measure
  - Compare
  - Compute
  - Correct
- Applications
  - Ball Mill, copper extraction
  - PCB Fabrication, multilayer
  - Chemical Mixing, $CuSO_4$

Elements of automatic control system

- The three functional elements needed to perform the functions of an automatic control system are:
  - A measurement element
  - An error detection element
  - A final control element

Process Operation

- First control systems required constant human involvement for maintaining process variables
- Controller replaced human intelligence with machine intelligence
- Remote sensors provide information to controller
  - Information signals (data) from sensors can be in the form of air/hydraulic pressure, or electrical activity
- Centralized remote control provided by Central Control Room

Industrial Control Classifications

- Industrial control system are often classified by what they control:
  - Motion control
    - Automatic control system that controls the physical motion or position of an object
    - Example: Robot arm (Welding, assembly operations)
  - Process control
    - One or more variables are regulated during the manufacturing of a product
    - Two categories:
      - Batch processing
      - Continuous process

Industrial Control Classifications

- The primary difference between process control and motion control:
  - The control method that is required
  - Process control:
    - Emphasis on sustaining a constant condition of a parameter
  - Motion control
    - Changes in the demand are constantly changing
    - The system follows the changes in the desired input signal as closely as possible.

Open- and Closed-Loop Systems

- An industrial control system maintains one or more variables in a production process at a desired value.
- Variables:
  - Pressure
  - Temperature,
  - Fluid and solid (grain) level
  - Flow rate
  - Composition of materials
  - Motor speeds,
  - Position (robotics arm)

Process Variables

- Variable
  - Physical quantity that can be measured, altered, transmitted, recorded
- Process
  - Series of actions directed to some end
- Measurement
  - Act of reading a value (datum-data) at a certain time
- Control
  - Regulation
- Process Variable
  - Current status measured of process under control
  - Actual value detected by a sensor as process takes place
- System
  - Group of interacting, interrelated, or interdependent elements forming a complex whole

Control System Terminology

- Controlled variable – process variable under control
- Set point – desired operating value of process variable
- Control point – actual measured value of variable
- Measurement – value of variable measured by sensor
- Offset – constant difference between set point and control point
- Primary element – sensor
- Transducer – converts energy from one form to another
- Controller – system component that adjusts system based on process variable measurements
- Error signal – difference between setpoint and control point
- Final control element – valve, pump, heater, etc. used to regulate a process

Open and Closed Loop Control

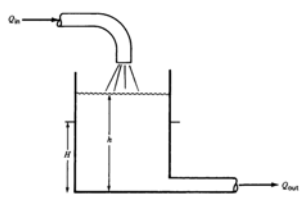
- Automatic control classification
- Open Loop
  - No feedback, typical of timed operations
- Closed Loop
  - Feedback, continuous adjustment/compensation

Open- and Closed-Loop Systems

- An industrial control system:
  - Open loop (manual control)
  - Closed Loop (Automatic control)

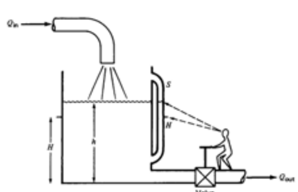
Open loop system

- The objective is to regulate the level of liquid in the tank, h, to the value H.
- Process variable:
  - Water level.



Open loop system

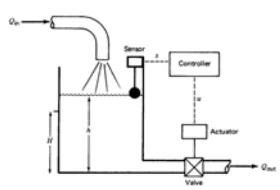
- A human can regulate the level using a sight tube, S, to compare the level, h, to the objective, H, and adjust a valve to change the level.



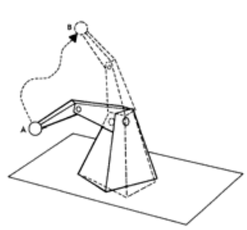
Open- and Closed-Loop Systems

- Open loop system
  - Simple
  - Must be manually balanced
  - Examples
- Closed loop system
  - Self-correcting and self-regulating
  - Used by most automated processes

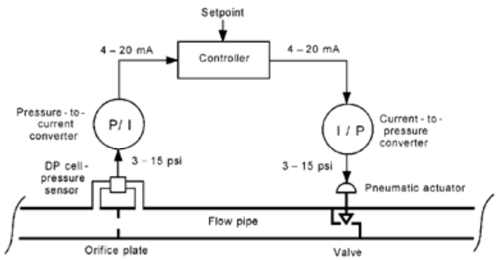
- An automatic level-control system replaces the human with a controller and uses a sensor to measure the level.



- Servomechanism-type control systems are used to move a robot arm from point A to point B in a controlled fashion.



The physical diagram of a control loop. i-p transmission signals.

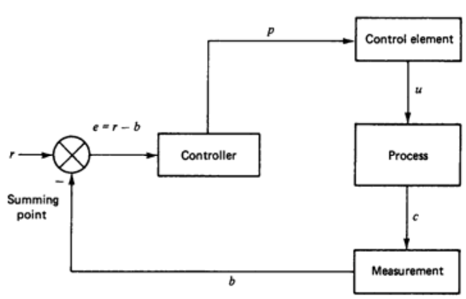


(a) Physical diagram of a process-control loop

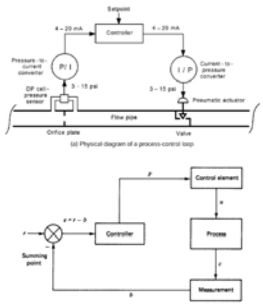
The physical diagram of a control loop. i-p transmission signals.

- i - current
- p – pressure
- DP – Differential Pressure
- mA – unit of electric current intensity
- i-p – current to pressure

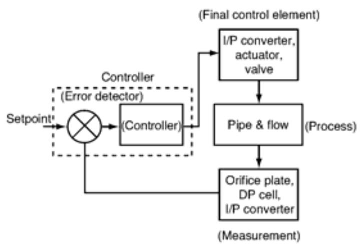
This block diagram of a control loop basic elements and signals involved.



These are the physical and block diagrams of a control loop



The physical diagram of a control loop. i-p transmission signals.

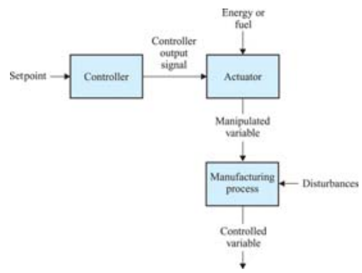


(b) Block diagram of the process-control loop

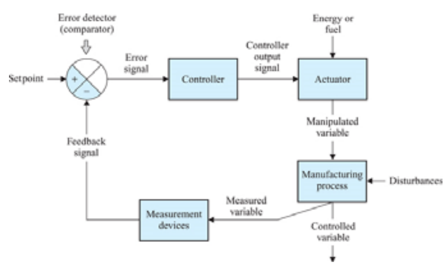
Elements of Open- and Closed-Loop Systems

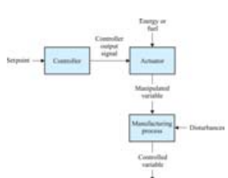
- Common terms:
  - Controlled variable or process variable
  - Measured variable
  - Measurement device
  - Feedback signal
  - Set-point
  - Error detector
  - Error signal
  - Controller
  - Actuator
  - Manipulated variable
  - Manufacturing process
  - Disturbance

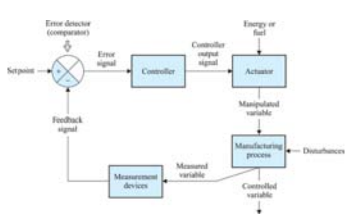
Open-loop block diagram elements, input/output signals, and signal direction



Closed-loop block diagram elements, input/output signals, and signal direction



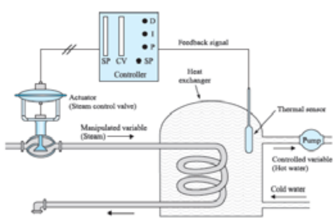




Feedback Control

- Error must exist before some corrective action can be made
- Causes of errors:
  - The set-point is changed
  - A disturbance appears
  - The load demand varies
- Signals may be positive or negative

Practical Feedback Application
Heat exchanger



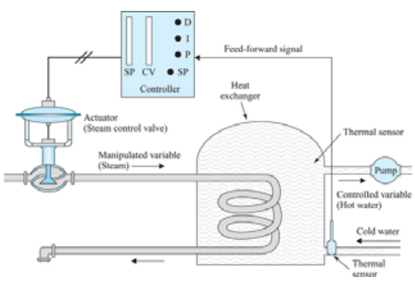
Dynamic Response of a Closed-Loop System

- Dynamic response:
  - Measure of loop's corrective action
- Factors:
  - Response time
  - Time duration
  - Static inertia of controlled variable
  - Leads to pure lag
  - Dead time

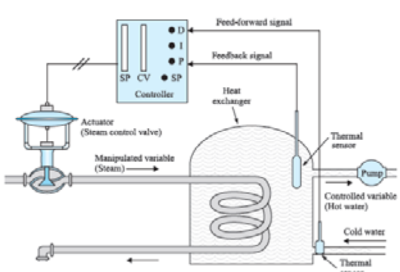
Feed-Forward Control

- Prevent errors from occurring
- Minimize not prevent
- Also use feedback control
- Typically used only in critical applications within the plant

Feed-forward control of a temperature control system



Feed-forward control loop with a feedback control loop



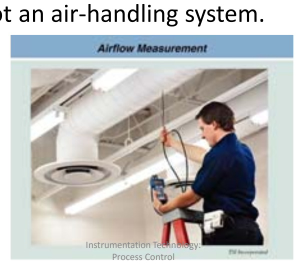
PRRACTICE

Process Operation

- A boiler operator is responsible for calibrating the instruments used to control a boiler.

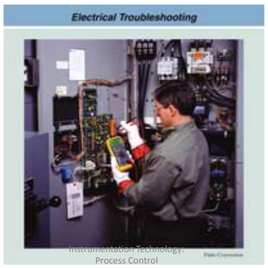
Process Operation

•An heating, ventilation, and air conditioning (HVAC) technician measures airflow to troubleshoot an air-handling system.



Process Operation

•An electrician is often required to trouble-shoot electrical systems related to instrument systems.



Process Operation

- Pneumatic controllers have visible internal components that make it easy to see how they work.
- Modern digital controllers are more versatile and reliable, but the internals are not as easy to see and understand.

Process Operation

•A modern transmitter can receive inputs from several types of instruments and sends signals in both digital and analog formats.

Measuring Process Variables

- Pressure
  - Force per unit area, P = F/A
- Example:
  - A tank with a bottom surface area of 10” by 12”, holds 25 lb of water.
  - What is the pressure at the bottom surface of the tank?
  - $P = F/A = 25lb/(10\ in*12in) = 25\ lb/\ 120\ in^2$
    $= 0.2083$ psi
  - Increasing depth, increases pressure
  - Investigation: P = F/A
    - Decreasing surface area, increases pressure

Measuring Level

- Level
  - Height of surface of volume being measured
  - Not volume, volume = area * depth; V =A * h
  - Just the depth (or height)
  - As level changes, pressure does too, so pressure can also be used to measure level, as well as volume
  - ΔP transmitter
  - Gamma
  - Neutron
  - Ultrasonic

Measuring Flow Rate

- Flow Rate
  - Amount of liquid passing through an opening per unit time

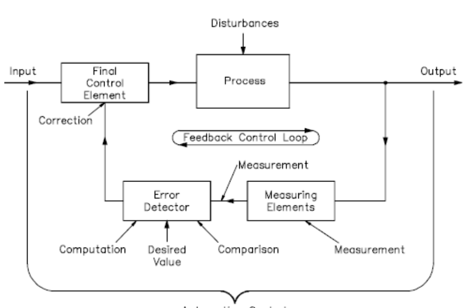
$$q = K \sqrt{\Delta P}$$

Standards organizations

•There are many industry and standards organizations that influence production operations.

SYNOPSIS

Functions and Elements in an Automatic Control System



Process Control Term Definitions Summary

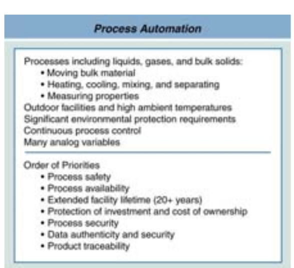
- A *control system* is a system of integrated elements whose function is to maintain a process variable at a desired value or within a desired range of values.
- *Control system input* is the stimulus applied to a control system from an external source to produce a specified response from the control system.
- *Control system output* is the actual response obtained from a control system.
- An *open-loop control system* is one in which the control action is independent of the output.
- A *closed-loop control system* is one in which control action is dependent on the output.
- *Feedback* is information in a closed-loop control system about the condition of a process variable.
- A *controlled variable* is the process variable that is maintained at a specified value or within a specified range.
- A *manipulated variable* is the process variable that is acted on by the control system to maintain the controlled variable at the specified value or within the specified range.

Process Control

- A low-water fuel cutoff is a level-measuring device that shuts down a boiler when the water level drops below the lowest allowed level.

Process Control

- Process automation refers to processes involving batch and continuous flow of liquids, gases, and bulk solids.


Process Automation

Processes including liquids, gases, and bulk solids:
- Moving bulk material
- Heating, cooling, mixing, and separating
- Measuring properties

Outdoor facilities and high ambient temperatures
Significant environmental protection requirements
Continuous process control
Many analog variables

Order of Priorities
- Process safety
- Process availability
- Extended facility lifetime (20+ years)
- Protection of investment and cost of ownership
- Process security
- Data authenticity and security
- Product traceability

Process Control

•Factory automation refers to processes usually involving piece flow of product.

Factory Automation

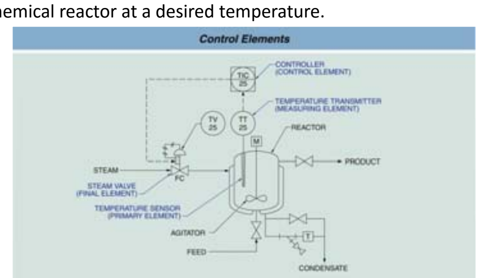
Synchronized manufacturing processes:
- Moving, aligning, transporting parts
- Mechanical operations
- Measuring dimensions

Compact plants and limited ambient temperature range
Limited environmental protection requirements
State detection and motion control
Binary values dominate measurements

Order of Priorities
- Productivity (speed, high clock frequencies, etc.)
- Low costs
- Real-time processing
- High positioning accuracy
- Scalability and flexibility
- Predictable/remote maintenance
- Product traceability
- Fast delivery of spare parts

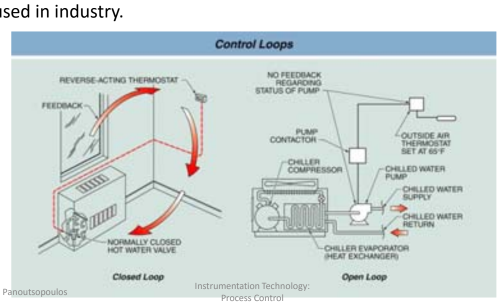
Process Control

•Control elements are part of a control loop used to maintain a chemical reactor at a desired temperature.



Process Control

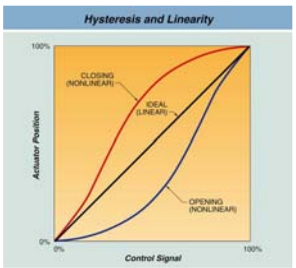
•Both open loop and closed loop control systems are commonly used in industry.



APPENDIX: HYSTERESIS

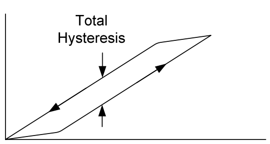
Process Control: Hysteresis

•Hysteresis is the property of a control element that results in different performance when a measurement is increasing than when the measurement is decreasing.



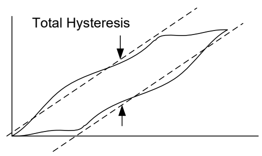
Explanation of hysteresis calculation

- Hysteresis is the measurement of the difference in Y offset of the values generated by the transducer as it measures in a positive going direction, and the same values as the transducer measures back down toward zero(the negative going values).
- Fig.: General hysteresis



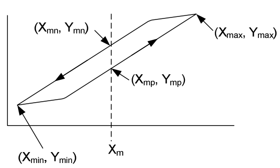
Explanation of hysteresis calculation

- In many cases the main portion of this curve does not work out to be a simple straight line offset in each direction.
- Non-linearity and sampling error tend to make the line less than ideal.
- Therefore the general case solution is to have two parallel lines, one passing through the main portion of the positive going values and one through the negative.
- Fig. Hysteresis of non-linear curves



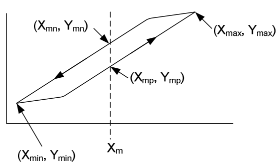
Explanation of hysteresis calculation

- The generation of these two lines generally requires some finesse and is not nearly as scientific as some would think.
- The calibrator must determine where the "main" portion of the curve is and then what line best fits through the positive going points.
- The second line then needs to be placed through the negative going set, keeping the same slope.
- The difference in Y intercept of these two lines then becomes the total amount of hysteresis. In a more simplified system, where the nonlinearity is less dramatic the calculation of the hysteresis becomes much simpler.
- In this simplified case the total hysteresis is the difference in y values compared to the total amount of y span.
- Fig. Definition of points.
- (n-negative, p-positive)



Explanation of hysteresis calculation

- The calculation of the hysteresis in this simplified condition occurs at the X midpoint of the curve. This point can be located with the following formula.
- Equation 1 Midpoint location
- Once the midpoint had been located, the two Y values (positive and negative going) can be obtained and the calculation becomes a simple plug and chug.
- Equation 2 Hysteresis calculation



$$X_m = \left(\frac{X_{\max} - X_{\min}}{2}\right) + X_{\min}$$

$$\text{Hysteresis\%} = \left|\frac{(Y_{mn} - Y_{mp})}{(Y_{\max} - Y_{\min})}\right| \times 100$$

Explanation of hysteresis calculation

- In some complex situations the curves may be so close that it is nearly impossible to differentiate, or the linearity is so bad that it simply swamps the amount of hysteresis.
- In these conditions a hysteresis of 0 is possible.
- Another unusual condition is where the negative going slope has so much hysteresis that it overlaps the positive going transition.
- Under these conditions the slopes of the positive and negative going portions of the curve have Y intercept values that are extremely large.
- Under these conditions the calculation, made either graphically or mathematically, using the difference between the slopes, could easily end up with a hysteresis of larger than 100%.
- Generally these types of huge hysteresis conditions are intentionally created for fine/course control inputs.

•