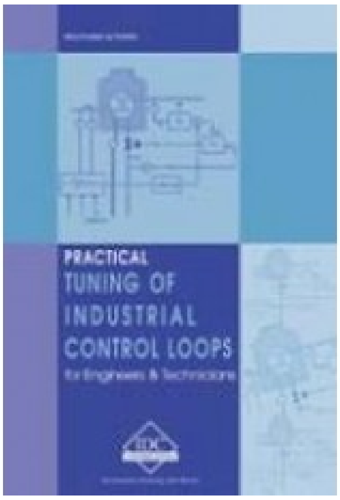
LT-E - Tuning of Industrial Control Loops



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Short Description

This manual covers the configuration and tuning of industrial control loops using a minimum of mathematics and formulas. Controllers need to be carefully matched to the process to work optimally; this matching procedure is called tuning. Controllers that are not correctly configured and tuned will not perform optimally and will not reduce variability in the process as they should. The aim of this manual is to provide the knowledge required to configure and tune a controller for optimum operation.

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An optimally tuned processed loop is critical for a wide variety of industries ranging from food processing, chemical manufacturing, oil refineries, pulp and paper mills, mines and steel mills. Although tuning rules are designed to give reasonably tight control, this may not always be the objective. Some thought needs to be given when retuning a loop as to whether the additional effort is justified as there may be other issues which are the cause of the poor control.

These issues will be discussed in some detail in the manual.

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First Chapter
An Introduction to Practical Tuning of Industrial Control Loops

1 Introduction

Learning objectives

As a result of studying this chapter, you should be able to:

- Describe the three different types of processes
- Indicate the meaning of a time constant
- Describe the meaning of process variable, setpoint and output
- List the different modes of operation of a control system

1.1 Introduction

In principle, most process control systems consist of a control loop, comprising four main functions, these being:

- A measurement of the state or condition of a process
- A controller calculating an action based on this measured value against a pre-set or control value (setpoint)
- A signal with a value that represents the result of this calculation being fed back from the controller to the process, which is to manipulate the process action
- The process itself reacting to this signal, and changing its state or condition.

In this manual, we will discuss the measurement of a process, control calculations based on this measurement and how the final result is used. Every process is unique and has different characteristics. Therein lies the first problem: the objective to achieve tighter and close control of the process. This places us in a dilemma as we do not know what that process is, but we cannot ignore it. The second problem is to identify where to start when the entire process is a loop. Do we start with measurement, or the controller? Fortunately, a solution to the first problem, that of the unknown process, gives us the solution to the second problem.

All processes must have a set of common parameters and dynamics; if they don't, every type of controller would have to be different and no common boundaries would exist.

The dynamics of each process, their type and magnitude, have to be understood before any attempt can be made in selecting the type of measuring device(s), the type of control system and finally the type of final control element.

Let us start by examining the component parts of the more important dynamics that are common to all process functions. This will be the topic covered in the next few sections of this chapter, and upon completion we should be able to draw a simple block for any process system. For example, we would be able to say "It is a system with capacitive and inertial properties, and as such we can expect it to perform in the following way", regardless of the precise details of the process.

To visualize the behavior of a system, block diagrams can be used to provide a visual description of the components. The two main symbols used are the circle and the rectangular block as shown in Figure 1.1.

The circle represents algebraic addition and subtraction. It is always entered by two lines but exited by only one line.

The rectangular block represents algebraic multiplication and division. It is entered and exited by only one line. The output is the product of the system function, which is symbolized inside the block, with the input.

The system function is the symbolic representation of how an input change affects the output for a particular process component.

Figure 1.1

Diagram of the summer and gain blocks

The steady state and dynamic behavior of a system can be determined by solving the differential equation that represents the system. Solving the differential equations is time consuming and a tedious task. The Laplace transformation technique is used for solving differential equations. In process control, Laplace transforms are commonly used to determine the responses to process disturbances.

Transfer functions are used as a tool for analysis of a control system. Each element or block of the control system has its own characteristic transfer function. Using individual transfer functions representing individual system elements can be combined, using algebraic methods to represent the overall control system.

1.2 Process dynamics

In order to match a controller to a process it is necessary to understand the process dynamic characteristics. The majority of processes can be described in terms of resistance, capacitance and dead-time elements, which determines the dynamic and steady state responses of the process to disturbances.

Resistance type processes

The most obvious illustration of a resistance type process is the pressure drop through pipes and other equipment, i.e. where there is some resistance to the transfer of energy or mass. These parts of the process are known as 'resistances'.

Figure 1.2

A capillary flow system illustrating the resistance (proportional) element

Figure 1.2 illustrates the operation of a capillary flow system where the flow is linearly proportional to the pressure drop. This process is described by a steady state gain, equal to the resistance (R). As the input (flow = m) changes instantaneously from zero to m, the output (head = c) undergoes an instantaneous change from zero to c = R x m.

This laminar resistance to flow is analogous to the electrical resistance (R) to current (i) flow as given by the Ohm's law, v = i x R.

In laminar flow, such as capillary flow, the resistance is a function of the square root of the pressure drop.

Flow processes usually consist of a flow measuring device and a control valve in series, with the flow (c) passing through both of them as shown in Figure 1.3.

Figure 1.3

Flow is a resistance (proportional) process

The block diagram illustrates that this is an algebraic and proportional (resistive) process. The manipulated variable (m) is the operation of the control valve, and (c) is the controlled variable; this being the flow through the system. A change in (m) results in an immediate and proportional change in (c).

The amount of change is a function of process gain or sensitivity K_a. Load variables are U_0 and U_2 the up and down stream pressures and any change of these results in an immediate and proportional change in the flow (c). The amount of change is proportional to their process sensitivity (K_B).
The overall process equation is

$$c = (K_a)m + (K_b)U_O - (K_b)U_2 + M_3$$

Capacitance type processes

Most of the processes include some form of capacitance or storage capability, either for materials (gas, liquid, or solids) or for energy (thermal, chemical, etc.). Those parts of the process with the ability to store mass or energy are termed 'capacities'. Thermal capacitance is directly analogous to electrical capacitance, which is defined by Faraday's law.
The capacitance of a liquid or gas storage tank is expressed in area units. These processes are illustrated in Figure 1.4. The gas capacitance of a tank is constant and is analogous to electrical capacitance.
The liquid capacitance equals the cross-sectional area of the tank at the liquid surface; if this is constant then the capacitance is also constant at any head.

Figure 1.4

Capacitance of a liquid or gas storage tank expressed in area units

Figure 1.5

Liquid capacitance calculation; the capacitance element

A purely capacitive process element can be illustrated by a tank with only an inflow connection such as Figure 1.5. In such a process, the rate at which the level rises is inversely proportional to the capacitance and the tank will eventually flood. For an initially empty tank with constant inflow, level c is the product of the inflow rate m and the time period of charging t divided by the capacitance of tank C.

Inertia Type Processes

Inertia effects are due to the motion of matter. They are most commonly associated with mechanical systems involving moving components, but are also important in some flow systems in which fluids must be accelerated or decelerated.

Resistance and capacitance are perhaps the most important effects in industrial processes involving heat transfer, mass transfer and fluid flow operations. The combined effect of supplying a capacity through a resistance is a time retardation. This is basic to most dynamic systems found in industrial processes.

Figure 1.6

Resistance and capacitance effects in a water heater

As a result of this time retardation, an instantaneous change in the input to the system will not result in an instantaneous change in the output. Rather, the response will be slow, requiring a finite period of time to attain a new equilibrium.

1.3 Process time constants

Combining a capacitance type process element, such as a tank, and a resistance type process element, such as a valve, results in a single time constant process. In a mathematical sense, the time constant is the future time necessary to experience 63.2% of the change remaining to occur, at any moment in the process.

The time constant is a measure of the rapidity of the response of the process. It can be characterized in terms of the capacitance and resistance (or conductance) of the process.

First order response

In the basic case of a first order response, the maximum rate of change of output occurs immediately after a step change in input. 63.2% of the total response is attained after one time constant. If the system continued to change at its initial speed of response, the maximum response rate, it would reach 100% of the output change in one time constant. A physical example of a first order process is an initially empty tank with a constant inflow and a valve controlled outflow.

Figure 1.7

A physical example of a first order process: a constant inflow and a valve controlled outflow

The general equation for such a process is a linear first order differential equation:

$$T \frac{dc(t)}{dt} + c(t) = Km(t)$$

Where:

T - Time constant of the process

K - Gain of the process

t - Time

c(t) - process output response

m(t) - process input response

Process elements of this description are common and are generally referred to as 'first order lags'. They may also be called 'linear lags' or 'exponential transfer lags'. Components with this response are characterized by the capacity to store material or energy and the dynamic shape of the response curve is described by a time constant.

Figure 1.8

First order response

In multiple time constant processes, say where two tanks are connected in series, the system therefore has two time constants operating in series. As the number of time constants increases, the response curves of the system become progressively more retarded and the overall response gradually changes into an S-shaped reaction curve. This curve is typical of the majority of processes.

Second order response

Second order processes result in a more complicated response curve. This is due to inertia effects and interactions between first order resistance and capacitance elements. They are described by the second order differential equation:

$$\frac{d^2 c(t)}{dt^2} + 2xw_n \frac{d\, c(t)}{dt} + w_n^2 c(t) = Kw_n^2 r(t)$$

Where,

w_n - natural frequency of the system

x - Damping ratio of the system

K - System gain

t - Time

r(t) - input response of the system

c(t) - output response of the system

The solutions to the equation for a step change in r(t) with all initial conditions zero can be any one of a family of curves shown in Figure 1.9. There are three possible cases in the solution, depending on the value of the damping ratio:

x < 1.0, the system is underdamped and overshoots the steady-state value.
If x < 0.707, the system will oscillate about the final steady-state value.
x > 1.0, the system is overdamped and will not oscillate or overshoot the final steady-state value.
x = 1.0, the system is critically damped. In this state it yields the fastest response without overshoot or oscillation.
The natural frequency term w_n is related to the speed of the response for a particular value of x. It is defined in terms of the 'perfect' or 'frictionless' situation where x = 0.0.
A large frequency tends to squeeze the response and a small frequency to stretch it.

Figure 1.9

Second order response: two time constants in series, and response curves of processes with several time constants

High Order Response

Time delays can be used to approximate high-order model dynamics. Any process that consists of a large number of process units connected in series can be represented by a high order response. This transfer function could represent a series of first order transfer functions. In practice, the mathematical analysis of uncontrolled processes containing time delays is relatively simple but a time

delay or a set of time delays, within a feedback loop tends to lend itself to very complex mathematics.
In general, the presence of time delays in control systems reduces the effectiveness of the controller. In well-designed systems the time delays (deadtimes) should be kept to the minimum.

1.4 Basic definitions and terms used in process control

As we will see in the later chapters, two of the most important signals used in process control are called
Process Variable or PV.
and the
Manipulated Variable or MV.

In industrial process control, the Process Variable or PV is measured by an instrument in the field and acts as an input to a controller, which takes action based on the value of it. Alternatively the PV can be an input to computer based hardware system and its value displayed in some manner so that the operator can perform manual control and supervision.

The variable to be manipulated, in order to have control over the PV, is called the Manipulated Variable or MV. If we control a particular flow for instance, we manipulate a valve to control the flow. Here, the valve position is called the Manipulated Variable and the measured flow becomes the Process Variable.

In the case of a simple automatic controller, the Controller Output Signal (OP) drives the Manipulated Variable. In more complex automatic control systems, a controller output signal may not always drive a Manipulated Variable in the field. In practice, the term Manipulated Variable is rarely used. Most people involved in process control refer to the OP (output) of a controller and it is assumed that one knows the purpose of it.

The ideal value of the PV is often called Target Value. In the case of an automatic control, the term Set Point Value is preferred.

1.5 Types or modes of operation of available control systems

There are five basic forms of control available in Process Control. These are:

- On-Off

- Modulating
- Open Loop
- Feed Forward
- Closed loop

On-Off control

The most basic control concept is the On-Off control, as found in a household iron. This is a very crude form of control, which nevertheless should be considered as a cheap and effective means of control if a fairly large fluctuation of the PV (process variable) is acceptable.

The wear and tear of the controlling element (such as actuator, solenoid valve etc) needs special consideration. As the bandwidth of fluctuation of a PV is increased, the frequency of switching (and thus wear and tear) of the controlling element decreases.

Modulating control

If the output of a controller can move through a range of values, we have modulating control. It is understood that modulating control takes place within a defined operating range (with an upper and lower limit) only.

Modulating control can be used in both open and closed loop control systems.

Open loop control

We have open loop control if the control action (controller output signal OP) is not a function of the PV (process variable) or load changes. The open loop control does not self-correct when the PVs drift.

Feed forward control

Very often it is a form of control based on measured disturbances (feed forward control). It is a form of open loop control, as the PV is not used in the control action.

Figure 1.10

The feedforward control loop

Feedforward is a more direct form of control than finding the correct value of the manipulated variable (MV) by trial and error as occurs in feedback control. In feedforward the major process variables are fed into a model to calculate the manipulated variable (MV) required to control at setpoint (SP).

Figure 1.10 shows a block diagram of a feedforward control loop. The PV (controlled variable c) is a result of the control action.

In practice, feedforward control is used in combination with feedback or closed loop control. In hybrid feedforward control, the imperfect feedforward control corrects up to 90% of the upsets, leaving the feedback system to correct the 10% bias left by the feedforward component.

Closed loop or feedback control

We have a closed loop control system if the PV, the objective of control, is used to determine the control action. The principle is shown in Figure 1.11.

Figure 1.11

The feedback control loop

The idea of closed loop control is to measure the PV (process variable). Compare this with the SP (setpoint), which is the desired or target value; and determine a control action that results in a change of the OP (output) value of an automatic controller.

In most cases, the ERROR (ERR) term is used to calculate the OP value.

ERR = PV - SP

If ERR = SP -PV has to be used, the controller has to be set for REVERSE control action.

1.6 Closed loop controller and process gain calculations

Within this closed loop form of control there are two functional gain blocks, one being in the controller and the other in the process being controlled. The LOOPGAIN (K_{LOOP}) is the product of the Controller Gain (K_C) and the Process

Gain (K_P).

$$LOOPGAIN\ (K_{LOOP}) = K_C\ \ K_P$$

Where:

Process gain (K_P)

and

Controller gain (K_C)

As the total constituent parts of the entire loop consist of a minimum of 4 functional items; the process gain (K_P)

Controller gain (K_C)

the measuring transducer or sensor gain, K_S and finally the valve gain $K_{V.}$ The total loop gain is the product of these four operational blocks.

For ¼ damping, the ideal response where each oscillation has a ¼ of the amplitude of the previous cycle then:

$$KLOOP = (K_C\ \ K_P) = \ (\ ) \times\ K_S \times K_V = 0.5$$

1.7 Proportional, integral and derivative control modes

Most closed loop controllers are capable of controlling with three control modes that can be used separately or together

- Proportional control (P)
- Integral, or reset control (I)
- Derivative, or rate control (D)

The purpose of each of these control modes is as follows:

Proportional control...

This is the main and principal method of control. It calculates a control action proportional to the ERROR (ERR). Proportional control cannot eliminate the ERROR completely.

Integral control ... (reset)

This is the means to eliminate completely the remaining ERROR or OFFSET value, left from the proportional action. This may result in reduced stability in the control action.

Derivative control ... (rate)

This is sometimes added to introduce dynamic stability to the control LOOP.
Note:

The terms ***RESET*** for integral and ***RATE*** for derivative control actions are seldom used nowadays.

Derivative control has no functionality on its own.

The only combinations of the P, I and D modes are:

- P For use as a basic controller
- PI Where the offset caused by the P mode is removed
- PID To remove instability problems that can occur in PI mode
- PD Used in cascade control; a special application
- I Used in the primary controller of cascaded systems

1.8 An introduction to cascade control

Controllers are said to be "in cascade" when the output of the first or primary controller is used to manipulate the setpoint of another or secondary controller. When two or more controllers are cascaded, each will have its own measurement input or PV but only the primary controller can have an independent setpoint (SP) and only the secondary, or the most down-stream controller has an output to the process.

Cascade control is of great value where high performance is mandatory in the face of random disturbances, or where the secondary part of a process contains an undue amount of phase shift. Cascade control is one of the successful methods for improving the control performance and reducing the maximum deviation and integral error for disturbance responses. Cascade control has been used widely, as it is easy to implement and requires simple calculations.

The principal advantages of cascade control are:

- The secondary controller corrects disturbances occurring in the secondary loop before they can affect the primary, or main, variable.
- The secondary controller can significantly reduce phase lag in the secondary loop thereby improving the speed or response of the primary loop.
- Gain variations in the secondary loop are corrected within that loop.
- The secondary loop enables exact manipulation of the flow of mass or energy by the primary controller.

Figure 1.12

An example of cascade control

An example of cascade control is shown in Figure 1.12. The primary controller, TC, is used to measure the output temperature, T_2, and compare this with the setpoint value of the TC. The secondary controller, FC, is used to keep the fuel flow constant against variables like pressure changes.
The primary controller's output is used to manipulate the SP of the secondary controller thereby changing the fuel feed rate to compensate for temperature variations of T_2 only. Variations and inconsistencies in the fuel flow rate are corrected solely by the secondary controller: the FC controller.