普通高等教育"十二五"规划教材

Fieldbuses and Distributed Technologies for Process Control

过程控制与分布式技术和现场总线技术

朱晓青 主编

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·北京·

本书用英文较系统地介绍了有关过程控制的基本理论，以及运用分布式技术、现场总线技术实现过程控制的基本原理与方法。全书共分 7 章，分别介绍了过程控制与仪表系统的基本概念、分布式控制系统的基本原理与构成、SCADA、PLC 及智能仪表的基本构成、现场总线技术与现场总线仪表的基本原理与结构以及有关通信技术、可靠性技术和工程实践等方面的有关问题。

本书可作为控制理论与控制工程类专业研究生或自动化与测控类专业本科生相关双语课程教材或教学参考书，也可作为工程技术人员的参考资料。

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Introduction（前言）

过程控制是控制理论在工业生产过程中的主要应用，它以控制理论为基础，以各类仪表或计算机设备为载体，与生产工艺有机结合，构成过程控制系统。分布式技术的发展使得过程控制系统的实现更为灵活与可靠。现场总线技术则是数字化、智能化、网络化技术在现场仪表应用中的体现，也是信息化技术推动过程控制技术发展的新趋势。

本书用英文从过程控制技术、分布式技术及现场总线技术的基础概念出发，深入浅出地阐述了过程控制的基本原理、分布式技术的基本原理、现场总线的通信机制以及运用这些技术实现过程控制的基本方法等，力图使读者掌握过程控制系统的基本分析方法和运用分布式技术与现场总线技术实现过程控制的基本思路和方法。

本书具有如下特点：

（1）体系结构较为完整。本书内容涵盖过程控制与仪表系统、分布式控制系统、SCADA、PLC 及智能仪表系统、现场总线系统、通信技术、可靠性技术和工程实践等方面的有关问题。

（2）与工程结合且可读性强。全书图文并茂，虽为英文，但较为通俗易懂。各章自成体系又融会贯通，可方便读者有选择地学习。本书特别开设工程问题一章，就分布式控制系统或现场总线控制系统的工程应用进行讲解。

（3）既注重时代性又注重系统演变的历史。分布式控制系统是从仪表控制系统演变而来，现场总线控制系统主要就是现场仪表的总线化和配备先进的系统软件功能等。本书特别注重仪表技术与分布式控制技术和现场总线技术的有机结合，使读者能够形成较为完整的概念。

全书共分 7 章，第 1 章为过程控制与仪表系统的基本概念，第 2 章为分布式控制系统的基本原理与构成，第 3 章为 SCADA、PLC 及智能仪表的基本构成，第 4 章为分布式系统中常用的通信技术，第 5 章为分布式系统的可靠性技术，第 6 章为现场总线技术与现场总线仪表，第 7 章为工程实践。

本书是作者在多年工程实践以及教学与科研实践基础上，以跟踪国际上该领域发展前沿技术为前提形成的。由于作者水平有限，不足之处在所难免，希望读者指正。

编　者

2013 年 4 月

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Chapter 1

Introductions and Fundamentals

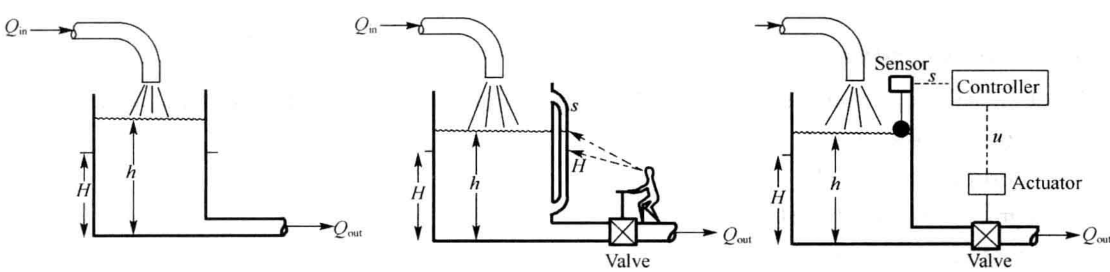
1.1 Fundamentals for Process control

1.1.1 Basic industrial control system

To succeed in process control the designer must first establish a good understanding of the process to be controlled. Since we do not wish to become too deeply involved in any typical industrial or process engineering, we need to find a way of simplifying the representation of the process we wish to control. This is done by adopting a technique of block diagram modeling of the process.

Example:

A process is liquid flowing into a tank at some rate Q_{in}, and out of the tank at some rate Q_{out}. The liquid in the tank has some height h. It is known that the higher the level, the faster the liquid flow out. As shown in Figure 1-1(a). The tank system can be regulated by a human, as shown in Figure 1-1(b). And the tank system can also be regulated by some instrumentations, as shown in Figure 1-1(c).



(a) process with no control (b) process controlled by man (c) process controlled automatically

Figure 1-1 Process and control

Most basic process control systems consist of a control loop as shown in Figure 1-2, there are four main components:

- 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 desired value (set point).
- An output signal resulting from the controller calculation, which is used to manipulate the process action through some form of actuator.
- The process itself reacting to this signal, and changing its state or condition.

Usually, two of the most important signals used in process control are called:

- Process variable or PV.
- Manipulated variable or MV.

In industrial process control, the PV is measured by an instrument in the field, and acts as an input to an automatic controller which takes action based on the value of it. Alternatively, the PV can be an input to a data display so that the operator can use the reading to adjust the process through manual control and supervision.

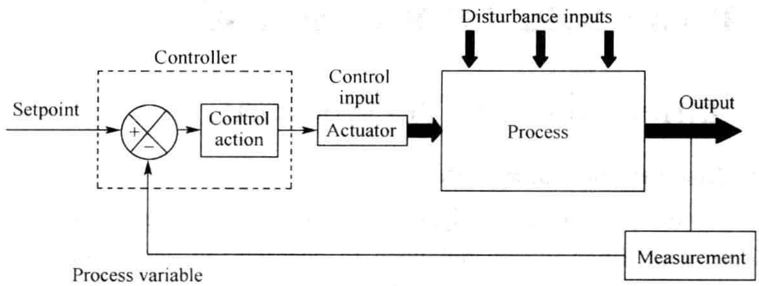


Figure 1-2 Block diagrams of the elements of a process control loop

The variable to be manipulated, in order to have control over the PV, is called the MV. For instance, if we control a particular flow, we manipulate a valve to control the flow. Here, the valve position is called the MV and the measured flow becomes the PV. In the case of a simple automatic controller, the Controller Output Signal drives the MV. In more complex automatic control systems, a controller output signal may drive the target values or reference values for other controllers. The ideal value of the PV is often called the target value, and in the case of an automatic control, the term Set Point (SP) value is preferred.

1.1.2 PID Algorithms

Most closed loop controllers are capable of controlling with three control modes, which 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 described as follows: Despite rapid evolution in control hardware, the proportional–integral–derivative (PID) controller remains the workhorse in process industries. The P action (mode) adjusts controller output according to the size of the error. The I action (mode) can eliminate the steady state offset and the future trend is anticipated via the D action (mode). These useful functions are sufficient for a large number of process applications and the transparency of the features leads to wide acceptance by the users. On the other hand, it can be shown that the internal model control (IMC) framework leads to PID controllers for virtually all models common in industrial practice.

Inside the proportional band the behavior of the 'textbook' version of the PID algorithm can be described as:

$$u(t) = K_P\left[e(t) + \frac{1}{T_I}\int e(t)\mathrm{d}t + T_D\frac{\mathrm{d}e(t)}{\mathrm{d}t}\right] \qquad (1\text{-}1)$$

Where $u(t)$ is the output of the controller;

$e(t)$ is the error between set point and process variable;

K_P is the position feedback gain;

T_I is the integral time;

T_D is the derivative time.

The following is the transfer function of the PID controller:

$$\frac{U(s)}{R(s)} = K_P\left[1 + \frac{1}{T_I s} + T_D s\right] \tag{1-2}$$

The PID algorithm can be arranged in parallel form or series form. The parallel form PID and series form PID are illustrated in Figure 1-3.

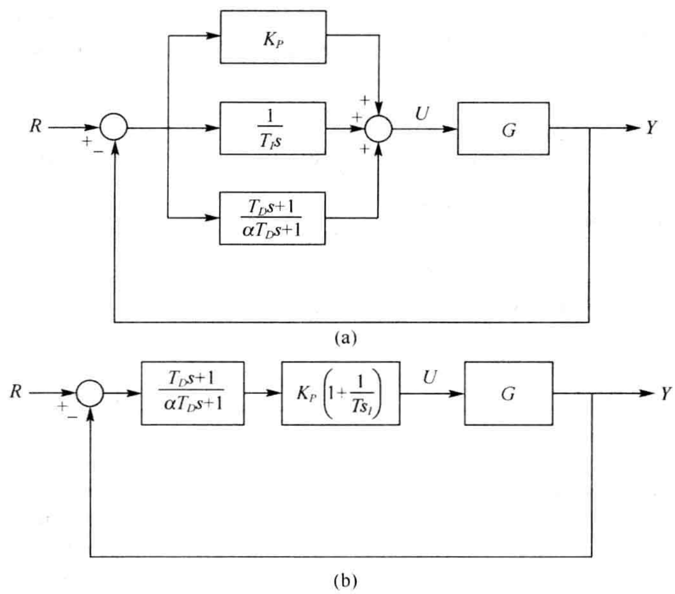


Figure 1-3 Parallel type (a) and series type (b) of PID controller

Usually derivative control has no functionality of its own. The combinations of the P, I and D modes are as follows:

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

Different control modes usually used in industrial are illustrated in Table 1-1.

1.1.3 Modifications of the PID Algorithm

The PID algorithm given by equation (1-1) or equation (1-2) is seldom used in practice because much better performance is obtained by the modified algorithm.

Because of possible discontinuity (step change) in reference signal that are transferred into error signal and result in impulse traveling through derivative channel and thus cause large control signals U_{PID}, it is more suitable in practical implementation to use derivative of output controller form or say differential in advance PID form. If PI-D structure (Figure 1-4) is used, discontinuity in

R will be still transferred through proportional into control signal $U_{PI\text{-}D}$, but it will not have so strong effect as if it was amplified by derivative element. Sometimes we also can use another structure of PID, which is the partial differential PID. In partial differential PID structure, the differential action be weakened somewhat, like Figure 1-5.

Table 1-1 Different types of control modes

Symbol	Description	Mathematical exp.	Properties
P-control model	The controller output is algebraically proportional to the error signal	$P=P_0+K_PE$ Where P=controller output; P_0= output at zero error; K_P= proportional gain; E=error signal	• It is characterized by a linear relationship between controllers I/O • Exhibits off set • Low stabilization time • When used alone it provides sufficiently large deviation
I-control model	This is a reset control model. The value of the controller output changes at a rate proportional to the error	$\mathrm{d}p/\mathrm{d}t = K_I E$ $P(t) = K_I \int E\mathrm{d}t + P_0$ $K_I=1/T_I$ K_I=Integral gain T_I= Integral time	• It eliminates offset • It shows oscillatory behavior • Large stabilization time
D-control model	Also be called rate control model. Controller output is proportional to the rate of change of error	$P=K_D\mathrm{d}E/\mathrm{d}t+P_0$ $K_D=T_D$ =Derivative gain	• Reduces oscillation • Improve dynamic performance • It improves no output when error is zero or constant
PI-control model	This model is combination of P and I	$P = K_P E + K_P K_I \int E\mathrm{d}t + P_0$	• Zero offset • Maximum deviation produced is larger than that produced by proportional but less than that of integral model • Eliminates offset
PD-control model	This model is combination of P and D	$P = K_P E + K_P K_D \mathrm{d}E/\mathrm{d}t + P_0$	• Lowest deviation • Small offset • Lowest stabilization time • It increases the overall stability
PID- control model	This model is combination of P ,I, and D	$P = K_P E + K_P K_I \int E\mathrm{d}t + K_P K_D \frac{\mathrm{d}E}{\mathrm{d}t}$	• It produces max. deviation which is large than that in PD • No offset • Stabilization time is longer than that of PD but smaller than PI

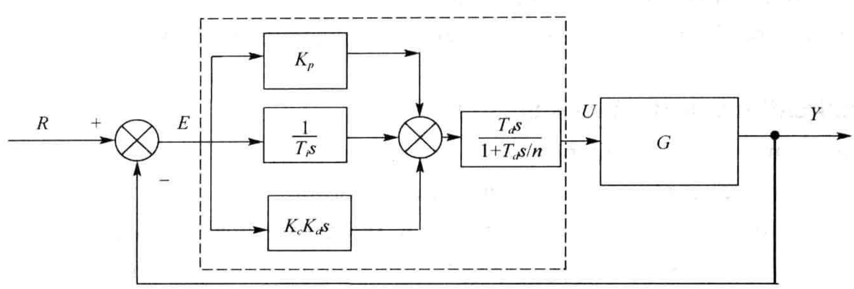


Figure 1-4 PI-D structure of controller

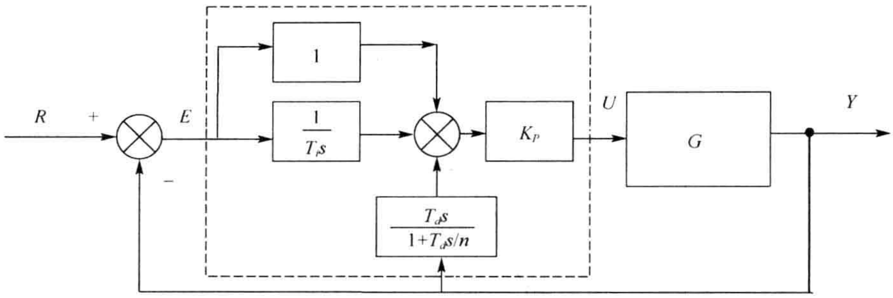


Figure 1-5 Another type of partial differential PID structure controller

In industrial applications, there are still other configurations such as integral separated PID form, set-point-on-I-only controller (I-PD) form, two-parameter form of PID controller, etc. usually are used.

1.1.4 PID Parameter tuning

Since the introduction of Ziegler–Nichols tuning in 1942, PID tuning has led to remarkable research activity over the past decades. From this we can conclude that there are many issues that have to be taken into account when designing a controller, e.g., load disturbance response, measurement noise, set point following, model requirements, and model uncertainty. It is also clear that there is a need for a variety of tuning methods; simple techniques that require little process knowledge as well as more elaborate methods that use more information about the process. Here we just introduce some of them.

(1) Based on (step) response (Ziegler-Nichols)

The step responses of a large number of process control systems exhibit a process reaction curve like that shown in Figure 1-6 which can be generated from experimental step response data. The characteristic of the system can be approximated by

$$\frac{Y(s)}{U(s)}=\frac{Ae^{st_d}}{\tau s+1} \tag{1-3}$$

The constant in equation(1-3)can be determined from the unit step response of the process. If a tangent is drawn at the inflection point of the reaction curve, then the slop of the line is $R=A/\tau$ and the intersection of the tangent with the time axis identifies the time delay $L=t_d$. Then the PID controller parameters are given in Table 1-2.

(2) Based on ultimate sensitivity

In the ultimate sensitivity method the criteria for adjusting the parameters are based on evaluating the amplitude and frequency of the oscillations of the system at the limit of stability, this is as shown in Figure 1-7. Here the proportional gain is increased until the system becomes marginally stable and continuous oscillations just begin. The corresponding gain is defined as K_u (called the ultimate gain) and the period of oscillation is P_u (called the ultimate period). The PID parameters are selected as shown in Table 1-3.

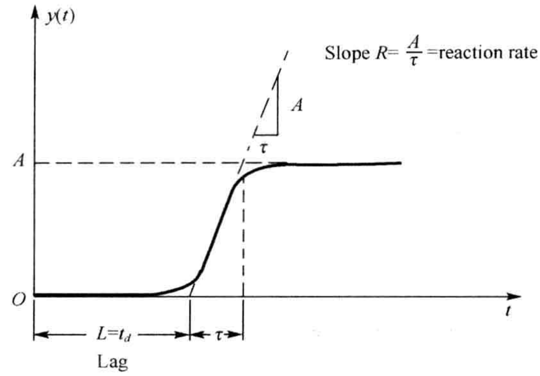


Figure 1-6 Step response curve

Table 1-2 PID parameters for step response method

	K_P	T_I	T_D
P	τ/AL		
PI	$0.9\tau/AL$	$3.3L$	
PID	$1.2\tau/AL$	$2L$	$0.5L$

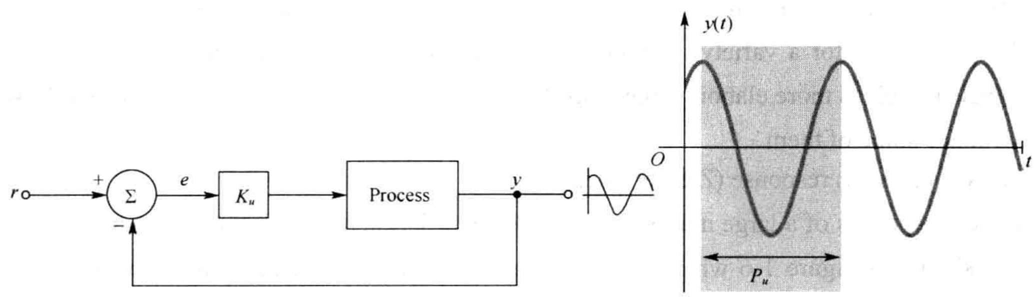


Figure 1-7 Ultimate sensitivity method

Table 1-3 PID parameters for ultimate sensitivity method

Type of controller	Optimum gain	Type of controller	Optimum gain
P	$K_P=0.5K_u$	PID	$K_P=0.6K_u$
PI	$K_P=0.45K_u$		$T_I=0.5P_u$
	$T_I=P_u/1.2$		$T_D=0.125P_u$

(3) Based on quarter decay ratio

In this method, the choice of controller parameters is designed to result in a closed-loop step response transient with a decay ratio of approximately 0.25. This means that the transient decay to a quarter of its value after one period of oscillation, as shown in Figure 1-8. The PID parameters are selected as shown in Table 1-4. We can see that the parameters in Table 1-3 are same as in Table 1-2.

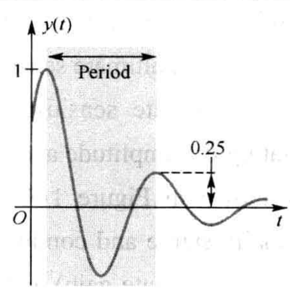


Figure 1-8 Quarter decay ratio method

Table 1-4 PID parameters for quarter decay ratio method

Type of controller	Optimum gain
P	$K_P=1/RL$
PI	$K_P=0.9/RL$ $T_I=L/0.3$
PID	$K_P=1.2/RL$ $T_I=2L$ $T_D=0.5L$

1.1.5 Configuration of PID

In practice, disturbance rejection is very important. The disadvantage to feedback only control is that a disturbance must be measured by the output variable before there is a control-system response. Using multiple measurements to the process can improve the response to disturbance. These methods include cascade control, feed-forward-control, ratio control, selective or override control, and split range control etc.

(1) Cascade control

Correction by feedback control is generally slow and results in long-term deviation from the set point. One way to improve the dynamic response to load changes is by using a secondary measurement point and a secondary controller; the secondary measurement point is located so that it recognizes the upset condition before the primary controlled variable is affected. Such approach is called cascade control. So the cascade control involves the use of multiple measurements and a single manipulated output. This allows disturbances in the secondary loop as well as non-linear valve and other final control element problems to be handled by the secondary PID Control block. In addition, the operator can directly control the secondary loop during certain modes of operation, such as startup. The requirements for cascade control are:

- The process dynamics of the secondary loop must be at least four times as fast as those of the primary loop.
- The secondary loop must have influence over the primary loop.
- The secondary loop must be measurable and controllable.

There are two ways to represent a cascade-control system: series cascade and parallel cascade. But the series cascade is the most common one. The series cascade control is shown as in Figure 1-9 and Figure 1-11, and the parallel cascade control is shown as in Figure 1-10. In cascade control system, the primary loop controls the primary variable, and the secondary loop (inner loop) controls the auxiliary variable.

In Figure 1-10 and Figure 1-11, R_1 is primary setpoint; R_2 is secondary setpoint; D_1 is primary controller; D_2 is secondary controller; G_1 is primary process; G_2 is secondary process; U_1 is primary manipulated input; U_2 is secondary manipulated output; Y_1 is primary output; Y_2 is secondary output; ω_1 is primary disturbance; ω_2 is secondary disturbance.

For the series cascade control system, if the secondary control loop (inner-loop) is much faster than the primary loop (outer-loop), so that

$$\frac{Y_2}{R_2}=\frac{D_2G_2}{1+D_2G_2}\approx 1 \tag{1-4}$$

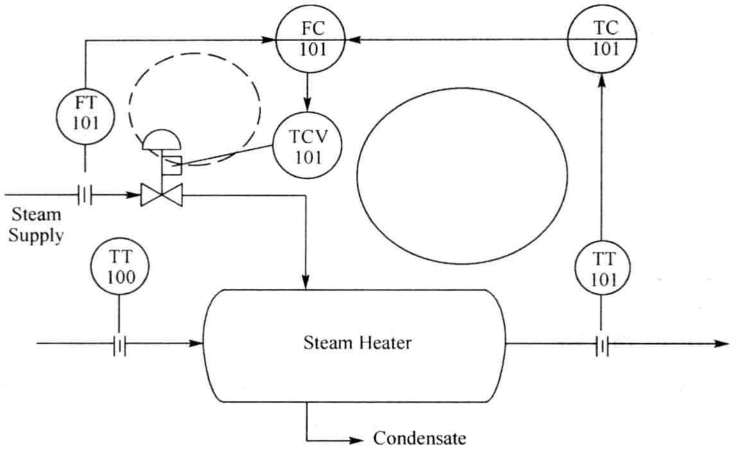


Figure 1-9 Cascade control system

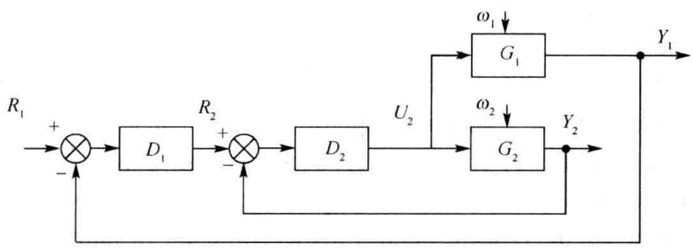


Figure 1-10 Block diagram of parallel cascade control

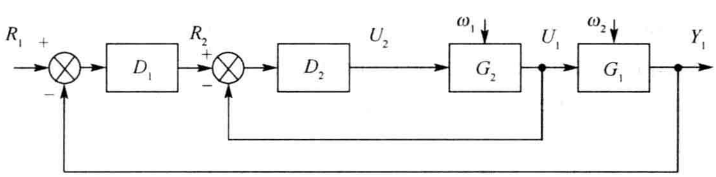


Figure 1-11 Block diagram of series cascade control

Then the closed loop transfer function for the primary loop is

$$Y_1 = \frac{D_1 G_1}{1 + D_1 G_1} R_1 \tag{1-5}$$

(2) Feed-forward-Control

When a disturbance affects a process under feedback control, it is necessary for a measured process output to change before corrective action is taken to change the manipulated input. It would be preferable to have a sensor that measures the disturbance and adjusts the manipulated input before the process output changes. That is the feed-forward-control. Feedforward control can also be used with closed-loop control to improve reference tracking performance. Feed-forward-control system is shown in Figure 1-12 and Figure 1-13.

In Figure 1-13, G_d is transfer function of disturbance, D_{ff} is feedforward controller.

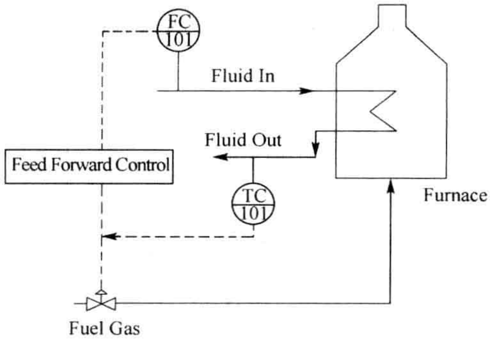


Figure 1-12 Feed-forward-control system

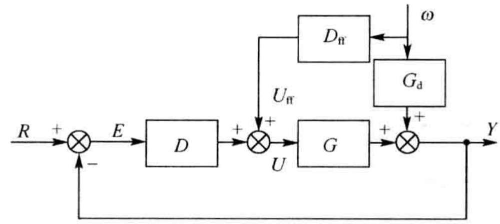


Figure 1-13 Block diagram of feed-forward-control (with feedback loop)

For the system in Figure 1-13, the output is

$$Y = \frac{D\,G}{1+D\,G}R + \frac{G_d + D_{ff}G}{1+D\,G}W \tag{1-6}$$

When R=0, and we select that

$$D_{ff} = -\frac{G_d}{G} \tag{1-7}$$

Then the inference of disturbance can be totally compensated.

(3) Ratio Control

Ratio control is similar to feed-forward-control, since both typically involve the measurement if a stream flow rate. Ratio control is often used in component blending problems. Ratio control system is shown in Figure 1-14 and Figure 1-15.

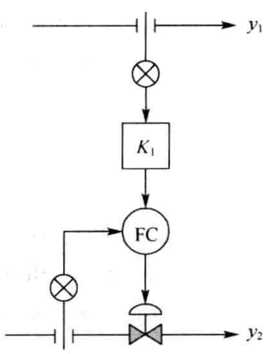


Figure 1-14 Ratio control system

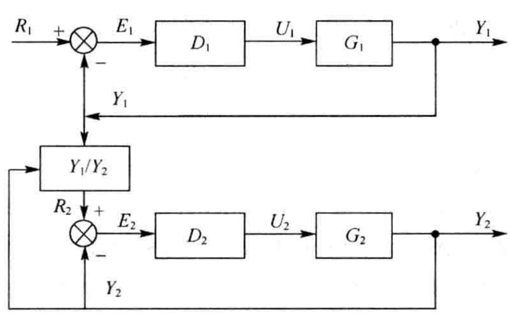


Figure 1-15 Block diagram of Ratio control

(4) Selective or override control

When there are more controlled variables than manipulated variables, a common solution to this problem is to use a selector to choose the appropriate process variable from among a number of available measurements. Selectors can be based on multiple measurement points, multiple final control elements, or multiple controllers. Selectors are used to improve the control system performance as well as to protect equipment from unsafe operating conditions. Selective control