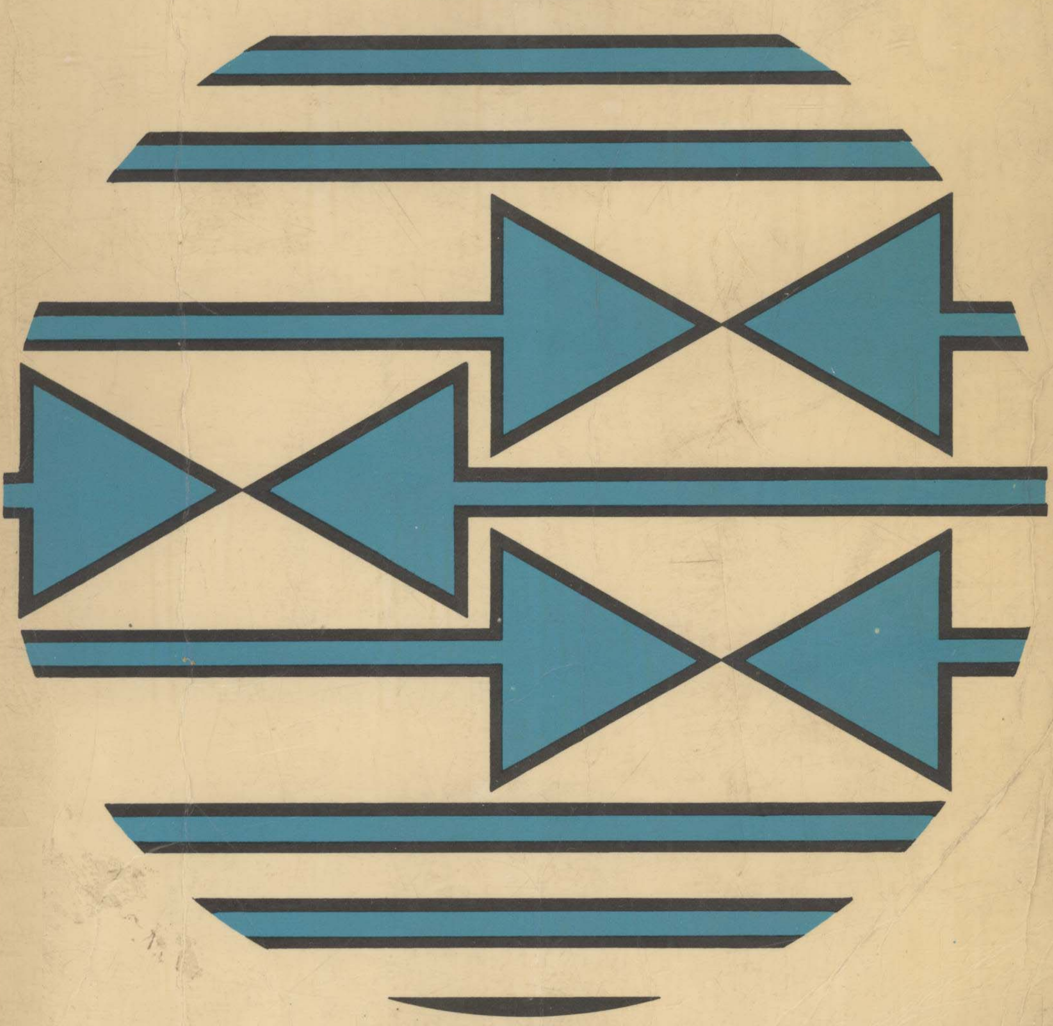
process control

A.Pollard



HEINEMANN CHEMICAL ENGINEERING SERIES

Process Control

For the Chemical and Allied Fluid-Processing Industries

A. POLLARD
B.Sc., C.ENG., F.I.CHEM.E., F.INST.F.,
M.INST.M.C., F.R.I.C.

Senior Lecturer in Chemical Engineering
and Process Instrumentation,
University of Leeds

HEB
HEINEMANN
EDUCATIONAL BOOKS
LONDON

Heinemann Educational Books Ltd

LONDON EDINBURGH MELBOURNE AUCKLAND TORONTO
HONG KONG SINGAPORE KUALA LUMPUR NEW DELHI
IBADAN NAIROBI LUSAKA JOHANNESBURG
KINGSTON/JAMAICA

ISBN 0 435 72561 0

First published 1971

Reprinted 1978

Published by Heinemann Educational Books Ltd
48 Charles Street, London W1X 8AH

Printed by photolithography and bound in
Great Britain by Biddles Ltd, Guildford, Surrey

PROCESS CONTROL FOR THE CHEMICAL AND ALLIED FLUID-PROCESSING INDUSTRIES

Preface

A sound knowledge of the basic principles underlying any particular branch of engineering is fundamental to its practical application in industry and to its further development. A study of the elements of process dynamics and control now forms an essential part of the education of the chemical engineer and is of value also to students in allied fields of fluid-process technology. The present volume covers the basic theory of the dynamics and control of linear process systems and the two main graphical methods (root locus and frequency response) available for process system analysis. The text is based almost entirely on courses given by the author over a number of years to undergraduates in chemical engineering and allied disciplines.

A knowledge of calculus, elementary differential equations, complex numbers, and the unit operations of chemical engineering compatible with the penultimate-year honours course is assumed. It is essential that the reader becomes familiar with the Laplace transform technique as a basic mathematical tool in systems analysis; the basic features of the technique are presented and the simple rules for direct and inverse transformation are easily acquired.

A detailed treatment of specific process systems and the instruments used in their control has not been included; such treatment tends to be descriptive rather than quantitative and often quickly becomes obsolete in this rapidly developing field. The more spectacular recent developments in process control, such as the application of direct digital control and optimalizing and adaptive systems, and the treatment of non-linear and multi-variable systems are given only relatively brief reference in view of the more fundamental material presented. The literature of process control is now so extensive that only a selected bibliography is included.

The author wishes to acknowledge many helpful discussions with his colleagues, particularly Mr F. H. Cass, and with students in the Department of Chemical Engineering in the University of Leeds. He is particularly obliged to Mr P. G. Myatt, of the Leeds Polytechnic, for much helpful advice and criticism during preparation of the manuscript. Finally, the book would not have been produced at all without the encouragement and forebearance of the author's wife, to whom he owes considerable thanks.

1971 A.P.

Nomenclature

A	area, amplitude, input element transfer function, term arising from finite gain in controller action equation
A.R.	normalized amplitude ratio
b	measured (feedback) variable
B	proportional band width
c	controlled variable, concentration, proportionality constant
c_p	specific heat capacity
C	capacitance
C_v	valve flow coefficient
d	differential operator
D	diameter, damping force, derivative action or control
e	base of natural logarithms
e	error, voltage
E	emissivity factor
f	function
f^*	sampled function
f_c	clamped function
F	force, function
g	gravitational constant, bellows spring constant
G	transfer function (forward path), specific gravity
G_c	controller transfer function
G_0	closed-loop M.R. at zero frequency
G_p	process transfer function, closed-loop peak magnitude
G_v	control valve transfer function
h	head or depth of liquid
H	measurement (feedback) transfer function, specific enthalpy
ΔH	heat of reaction
i	current
I	integral action or control, interaction factor
j	$\sqrt{-1}$
k	reaction rate constant, proportionality constant, thermal conductivity
K	proportionality constant, steady-state gain, overall gain, thermal diffusivity
K_c	proportional sensitivity, proportional gain
$K_{c\,\max}$	maximum proportional sensitivity (limiting stability)
K_g	controller gain
K_L	load gain
K_m	measurement gain
$K_{\max}$	maximum overall gain (limiting stability)

K_u	ultimate proportional sensitivity ($=K_{c\,\mathrm{max}}$)
K_v	valve sensitivity
l	distance, length
L	time delay, length, inductance
$\mathscr{L}$	Laplace transform operator
$\mathscr{L}^{-1}$	inverse Laplace transform operator
m	manipulated variable, mass, valve position
M	change in input variable, closed loop M.R., mass
M_p	closed loop M.R. relative peak height
M.R.	magnitude ratio
n	integer, real number
N	load element transfer function, slope of Ziegler-Nichols reaction curve
p	pressure, controller output signal, pole of function
Δp	pressure difference
P	applied force, period of oscillation
P_u	ultimate period of (continuous) oscillation
q	electrical charge, volumetric flow rate, heat flow rate
Q	heat flow rate
r	reference input signal, root of function or equation
R	resistance, gas law constant, lag ratio
R_d	derivative action resistance
R_i	integral action resistance
s	Laplace transform variable
$s_1, s_2 \ldots$	roots of polynomial or characteristic equation
S	spring force
T	time constant, characteristic time, sampling interval
T_d	derivative (action) time
T_i	integral (action) time
T_m	measurement time constant
u	load variable, disturbance signal
U	overall heat transfer coefficient
v	desired value signal, velocity
V	volume
w	mass flow rate
x	linear displacement, real part of complex number ($x + jy$)
X	thickness, length
y	imaginary part of complex number ($x + jy$)
z	zero of function, z-transform variable
α	damping factor, closed loop phase angle, derivative action phase advance
β	damped frequency
β_0	undamped (natural frequency)
γ	controller phase shift
δ	unit impulse
Δ	finite difference operator

ε	expansion factor, specific internal energy
ζ	damping ratio
θ	temperature
θ_d	desired value temperature
θ_i	input signal, input temperature
θ_o	output signal, output temperature
$\bar{\theta}$	design temperature (normal steady-state)
λ	integral action phase lag
μ	viscosity
π	pi (3.141 . . .)
Π	product
ρ	density
σ	Stefan-Boltzmann radiation constant
Σ	summation
ϕ	angle, phase angle
ψ	phase lag, angular displacement
ω	angular frequency (rads/unit time)
ω_c	critical frequency at 180° phase lag
ω_{co}	cross-over frequency
ω_n	natural frequency
ω_r	resonant frequency
∂	partial differential operator

Abbreviations for Units

	SI		British-American
°C	deg. Celsius	Btu	British thermal unit
J	joule	°F	deg. Farenheit
K	deg. Kelvin	ft	foot
kg	kilogramme	gal	gallon (UK)
m	metre	h	hour
N	newton	in	inch
s	second	lb	pound (mass)
W	watt	min	minute
		lbf/in^2	lb(force)/in^2(gauge)
		°R	deg. Rankine

Prefixes

k	kilo ($\times 10^3$)
m	milli- ($\times 10^{-3}$)

(See Mullin, *The Chemical Engineer*, September 1967)

Contents

Chapter 1: Introduction to Process Control

Automatic control is now widely used in many different fields ranging between such diverse applications as the automatic piloting of aircraft to the control of temperature in the domestic oven. In the analysis of problems within this range, an understanding of the basic principles is of primary importance since these same principles can be generally applied to any control problem regardless of variations in physical or mechanical detail. Differences between individual problems arise principally from the number, scale, and complexity of the relationships of the variables involved in the particular situation.

In this introduction the basic principles will be reviewed and ultimately considered with respect to the control of industrial processes typical of the chemical and allied fluid-processing industries, i.e. what is usually referred to as *process control*, as distinct from *position control* or *servo-operation*, which is the other major branch of automatic control engineering.

A process may be defined as simply an advance to some particular end or objective, which is achieved in all but the simplest cases by some orderly pattern or sequence of events or operations. In the chemical industry, where process control finds its widest applications, the process consists of the chemical engineering operations necessary to convert one or more raw materials into finished products, often with the simultaneous formation of by-products which may have to be separated from the desired end-product. Processing action, however, may be given a much wider interpretation on the simple definition given above. The movement of material from storage to a point of use and the transfer of components between stages of manufacture are processing actions. A process may be carried out on human beings; the training of individuals for some particular task or the education of students are processes in the sense that an orderly pattern of operations must be followed to attain the required objectives. Processing is also carried out on paper-work, as in accounting, design, etc. and in some of these fields the computer is already taking over the data-processing operations from individuals. However, such applications which involve the reaction of the human element in the achievement of the process objective form a natural branch from the purely mechanical field, and are not normally included as branches of process control but are regarded as the special field to which the name *cybernetics* has been applied.

In general, if a process is to be worthwhile it must be carried out efficiently. Efficiency may be defined in a number of ways depending upon the nature of the particular process, but in the final analysis the definition will usually be based on economic factors. To maintain efficiency, control of the process operations is necessary at every stage, and in all but the very simplest of processes this control cannot be exercised by purely manual means—the required efficiency cannot be maintained by human endeavour alone. The manual operator, at the very least, must usually be provided with some instrumental assistance to measure the variables in the process. Process instrumentation, or the measurement of process variables, is a very important division of the field of process control.

The operation of a process calls for certain events to take place; these events were originally manual operations and it is convenient still to refer to them as 'manipulations'. The manipulations necessary for a particular process may be quite simple or very complex. One person or several may be called upon to apply purely mechanical skills to the moving of levers, the adjustment of control valves, etc., or all or part of these operations may be carried out automatically by suitable apparatus.

The important feature common to all processes is that a process is never in a state of static equilibrium for more than a very short period of time. A process is a dynamic entity subject to continual upsets or disturbances which tend to drive it away from the desired state of equilibrium; the process must then be manipulated upon or corrected to drive it back towards the desired state. Manipulation is in itself a disturbance of the process, a correction is simply a manipulation to oppose the effect of some previous disturbance. Both disturbances and manipulation are events arising externally to the process. Some disturbances bring about only transient effects in the process behaviour; these pass away and may never occur again. Others may apply cyclic or periodic forces which make the process respond in a cyclic or periodic fashion. Most disturbances are completely random with respect to time and show no repetitive pattern; thus their occurrence may be expected but cannot be predicted at any particular time.

Process disturbances occur in many and varied ways. Raw materials for manufacturing processes are supplied in batches which may not be truly homogeneous so that the properties of the material may change as it enters the process. Machinery and plant do not run smoothly for indefinite periods but show a gradual deterioration in performance; plant may be affected by climatic conditions such as changes in ambient temperature and pressure, changes in cooling water temperature, and so on.

As has already been pointed out, an operating process is never static. Material or energy is always flowing and whilst it is possible to visualize a steady-state equilibrium, as is usually assumed in the design of continuously operating process plant, in practice this ideal state is rarely attained in operation except for very short periods. The reaction of the process under operating conditions is dynamic, and consequently it is necessary to study the dynamic reactions of processes which are to be controlled.

The Control System

The starting point in any control system is the particular variable which it is necessary to control to achieve some desired measure of the efficiency in the particular process. A process, of course, is never designed with the object of controlling a particular variable; rather more logically a process is designed for a particular objective or output and it is then found, sometimes by trial and error but more usually by inference from previous experience, that control of a particular variable associated with some stage of the process is necessary to achieve the desired efficiency.

The output of the controlled system is the value of the particular variable being controlled, and this will not necessarily be the same as the output of the process. The process output is obviously a dependent variable, since its value depends on the operation of the process and the manipulation of the inputs to the process. Whilst the process output may be almost any physical quantity, the output of the control system associated with the process need not be a product from the process in the usual sense. The output of the control system is more usually a variable associated with the process operation which determines in some way the efficiency of the process in reaching the desired end. For example, the temperature or pressure in a chemical reactor may determine the efficiency of operation of the reactor in producing products of the required specifications; hence one or both of these variables would be used to control the operation and so would be the outputs of one or two control systems. In the latter case the two systems might be completely independent of each other or they may interact with each other in certain ways. Generally in process control, the controlled variable is one of the more usual process variables, i.e. temperature, pressure, fluid flow rate, or liquid level, but could quite conceivably be almost any other physical property of the materials or the environment such as the composition of a material stream, density, pH, viscosity, speed, etc.

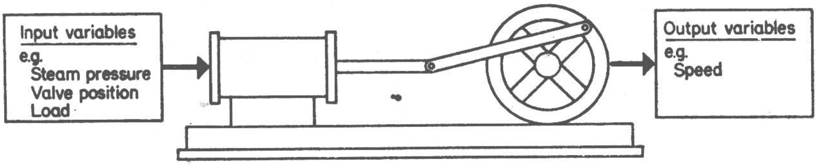


FIGURE 1–1. Steam engine input and output variables

It is more illuminating at this stage to look at some practical processes where the properties and effects are fairly obvious, rather than to discuss generalities. The first process to be considered is a steam engine, illustrated in Figure 1–1. Here is a process—the engine—and associated with it a number of variables which can be grouped initially into two categories, 'input' and 'output' variables. The former are independent variables; their values or magnitudes are determined by factors independent of the process. Some of the input variables can be manipulated, i.e. the values can be changed at will by a process operator (it is immaterial at this stage whether the operator is manual or automatic). Other input variables are not capable of being manipulated but their values are determined by outside agencies or natural phenomena. A change in the value of any input variable will affect the operation of the process in some way or other and will ultimately lead to changes in the values of some or all of the output variables.

These latter are not independent variables but are determined by the values of the input variables and the conservation balance of the material and/or energy flows into and out of the process. Generally one of the dependent output variables will represent, either directly or indirectly, the primary objective of the process operation, and this would be selected as the controlled variable, i.e. the process variable which must be held at a certain value or within certain limits if the process is to be operated efficiently and the required objective attained. In a rather similar way, in the majority of cases one of the input variables will have a more direct and immediate effect on the operation of the process and so also on the values of the output variables than will any of the others, and this particular variable would be chosen as the one to be manipulated to control the process through the selected output variable.

The steam engine presents a relatively straightforward picture. The object of the process is to convert the pressure energy of the steam into mechanical energy for a particular purpose which may be to raise a load or to propel a vehicle. The output variable immediately indicative of the engine's performance as a power unit is the speed of the output shaft, and the operation of the process of power conversion is then controlled on the basis of the engine speed. The primary input variable which has the most direct influence on the engine speed is the rate of flow of steam to the cylinders, but this in turn is determined by the restriction to the flow imposed by the usual regulating valve and the pressure drop across the valve, which again is a function of two other variables, the steam supply pressure and the engine back pressure. Of these, the variable which it is simplest and easiest to manipulate is the restriction imposed by the valve, and the speed of the engine is almost invariably controlled by manipulation of the position of the steam inlet valve.

It must be noted that other variables can also change the engine speed and these, by definition, must also be input variables. The steam supply pressure which partly determines the pressure drop across the valve and hence the steam flow through the valve has already been mentioned. Similarly, if the engine is required to do more work by an increase in the load on the output shaft, it will tend to slow down. An increase in friction in the piston or bearings due to lack of lubrication will have a similar effect. These are all input variations even though the load on the engine is concerned with the output of the process. For convenience a distinction can be drawn between *supply* and *demand* disturbances, i.e. those on the input and output sides of the process. A change affecting the steam pressure from the boiler is a supply disturbance, changes in the load on the output shaft are demand disturbances.

It will be noted that changes in the value of any input variable, as defined, will lead to a subsequent change in the output variable, but in each case the selected manipulated variable, i.e. the position of the steam valve, can be used to correct for the disturbance by admitting more or less steam as required. It will also be noted that selection of the steam valve position as the manipulated variable is not unique, and that other input variables could be manipulated to provide the necessary correction to a disturbance. For example, the steam valve could be dispensed with and the steam flow regulated by manipulation of the steam supply pressure through the boiler. This would be a less effective method as it would involve operating the boiler as part of the engine process and would introduce more input variables affecting the performance of the boiler. In a similar way the speed could be controlled by manipulating part of the load, by effectively applying a brake to the output shaft to use up any excess power following a reduction in the working load or an excess flow of steam. Again this can be seen to be less efficient and obviously less economic than manipulation of the steam flow by means of the valve.

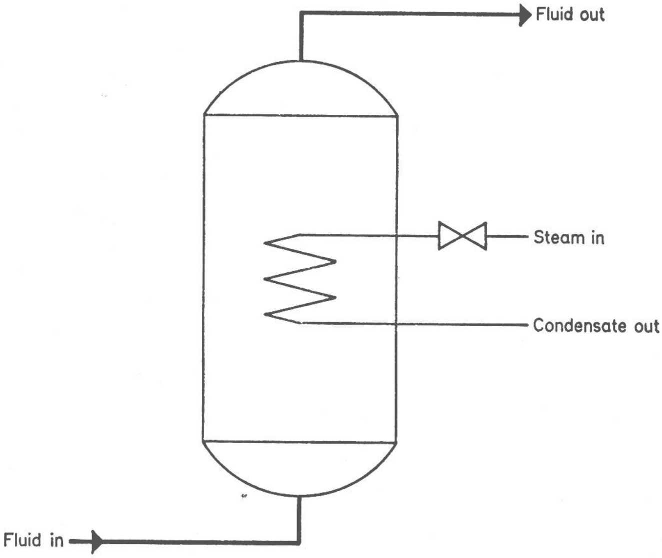


Figure 1–2. Fluid heater

A second process example is the fluid heater shown in Figure 1–2, in which the objective is to maintain a supply of heated fluid. Here again is a fairly obvious choice of both controlled and manipulated variables. That which is most indicative of the aim of the process and the efficiency of achievement is the temperature of the fluid leaving the heater, and the process would then be controlled by control of the output temperature. The input variable with the fastest and most direct reaction on the outlet temperature is the heat flow rate into the heater but, as in the previous example, two or more input variables may again be involved. If steam or some other heat transfer medium is used, the manipulated variable may again be the position of a flow regulating valve with the supply and back pressures as additional input variables. If the heating is by electricity then the position of a rheostat or variable transformer would be manipulated with the supply voltage as an additional variable. Rather less practical would be to control the output temperature by manipulating the flow of the fluid through the heater, with the heat supply as a completely independent variable. Supply disturbances already noted are the heating medium pressure or voltage; additionally the fluid inlet temperature is an additional input variable, and also in this case ambient conditions on the outside of the heater (temperature, air movement, etc.) are other possible sources of disturbance since these determine the magnitude of the heat losses from the apparatus. On the demand side the major and most probable disturbance is the flow rate of the heated fluid through the heater.

To sum up at this point, each process or process operation will have associated with it a number of variables which are independent of the process and/or its operation and which are likely to change at random. Each such change will lead to changes in the dependent variables of the process, one of which is selected as being indicative of successful operation. One of the input variables will be manipulated or adjusted in value to cause further changes in the output variables to restore the original conditions. These are quite general statements illustrative of the two examples discussed, and are of general application to any process. If not applicable in this way, then either the process does not require to be controlled because there are no input variables to cause changes in output, or the process cannot be controlled because no one input variable can be manipulated.

Having decided on a controlled variable which will be indicative of the process operation and which will normally require to be held at a certain level, the *desired value*, and a manipulated variable which is capable of affecting the operation of the process and leading to a change in the controlled variable, it is now necessary to consider the imposition of corrective action on the process.

The correcting, or controlling, device will initially require two elements, an input element by which the desired value may be introduced and an output element which will manipulate the appropriate variable. The former is basically nothing more than a pointer which can be set on a scale of desired values of the controlled variable; the output element is usually some form of valve used to regulate the rate of flow of material or energy which is the manipulated variable, as in the two examples considered. The two elements thus permit the pointer to be set on the scale to define a certain value of the controlled variable, and this in turn will set the valve at a certain position, permitting a certain flow into the process. Thus, in the case of the steam engine, a certain flow of steam is passed by the valve which permits the engine to run at a certain speed as dictated by the flow of steam and the other input variables. The only further requirement is the calibration of the scale of the input element to correlate with the actual values of the controlled variable.

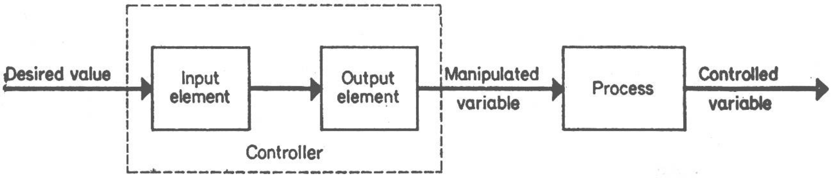


Figure 1–3. Open-loop control

This forms a type of control system as shown in Figure 1–3, which, for reasons which will be apparent later, is known as an *open-loop* system. As a control system it cannot, however, be very effective except in certain special cases. The system will fail in most applications because no account is obviously taken of the other input variables apart from the manipulated variable. All other input variables are perfectly free and can change in a completely random manner; any such change will upset the correlation between the controlled variable and the input element. A little consideration will show that any such correlation can only exist under one condition of load, i.e. if all the input variables are constant. If any input variable changes there will be a consequential change in the controlled variable and in this system the manipulated variable will not be adjusted to apply any correction. Another line of development must then be pursued.

There are two possible ways of improving the situation. From the previous discussion it will be appreciated that a change in any input variable can be corrected by a change in the manipulated variable. If the load on the engine is increased, the steam valve can be opened to admit more steam and thus maintain the engine speed. It is therefore possible in principle to use another input element to effectively measure the load on the engine and to use this to make an appropriate correction to the output element (the valve), so making the required change in the manipulated variable when the load changes to maintain the desired value of the controlled variable. This principle of *load-change compensation* is, however, applicable to changes in only one source of disturbance, and the method would strictly have to be applied separately to every individual input variable which could affect the process. This would require a very complex system and in practice this technique is rarely used in the form described.

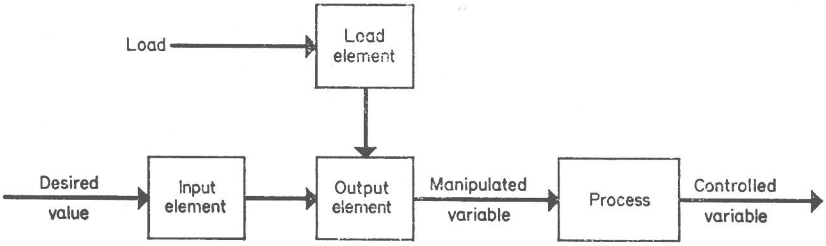


FIGURE 1–4. Open-loop load compensation

It is, however, being increasingly used in conjunction with the alternative *closed-loop* system of control as a compensation for the primary load disturbance affecting a system, under the name of *feedforward control.*

Closed-loop Control

The alternative method of dealing with the problem of external disturbances is relatively simple, so much so that it is the technique which is almost universally employed in practice to control any operation. The principle is to use the effects of the disturbances on the controlled variable to adjust the manipulated variable and so correct for the disturbance. In other words, since the disturbances are bound to happen, let them affect the process and so cause changes in the controlled variable but now use these changes, i.e. the departures from the desired value of the variable, to adjust the manipulated variable and so correct for the effect of the disturbance. The source or cause of the disturbance is ignored; only the effects on the controlled variable are used to apply the correction.

This now introduces the vitally important principle of *feedback*. The desired value of the controlled variable is, as before, set on the scale of an input element to provide an input signal, which may be symbolized by θ_i. This has now to be compared to an output signal, θ_o, which is effectively the actual value of the controlled variable at the time so that any difference between the two signals, which represents the departure of the controlled variable from the desired value, can be used to adjust the output element to change the manipulated variable and so apply the correction to restore the controlled variable to the desired value. Initially then, before the signals can be compared, the value of the output signal—the controlled variable—must be 'fed back' from the output side of the process to the controlling device, and this brings into being a *closed-loop* system, as shown in Figure 1–5. The purpose of the controller is now to make the output signal, θ_o, equal to the input, θ_i, and the logical step is to use the *difference* between the two at any time, which may be termed the *error* or *deviation* in the system, to generate the corrective action. A further element is now required in the controller in the form of an error discriminator (ε), which effectively subtracts θ_o from θ_i. The input to a system is conventionally