PRINCIPLES OF INDUSTRIAL PROCESS CONTROL

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FOREWORD

The last thirty years have been a period of great progress in the field of automatic control and automatic regulation. Automatic positioning controllers or servomechanisms are now used in the rapid and accurate control of airplanes, guns, and other fighting equipment.

Automatic control of industrial processes has been of equally great importance in speeding up the production of the many materials necessary in the fighting of a modern war. To mention one example, the synthetic-rubber program would have been impossible without the use of a multitude of automatic temperature, pressure, flow, and liquid-level controllers.

In applying automatic control to industrial processes, however, there are certain fundamental principles which apply to the operation of a process when under automatic control, as well as to the functioning of a servomechanism and its positioned element. This book is primarily devoted to the description and explanation of these fundamental principles.

The author has done an admirable job of drawing together the many loose ends in the literature on automatic control. The complete control system is divided into four elements; the measuring means, the controller mechanism, the final control element, and the process. The pertinate quantities are carefully defined, and appropriate lag coefficients and time constants are used in a treatment of the dynamic characteristics of control systems. Experimental lag coefficients are given for many industrial measuring elements. A number of controlled response curves are given and are used to illustrate the effects to be expected when adjusting a controller on the job. The theory of automatic control is considered with principal emphasis on the controlled and uncontrolled process response curves. The reaction rate-lag method is used to calculate controller settings and reaction rates, and lags are given for a number of representative processes. The cycling period method of setting the reset rate and rate-time controller adjustments is carefully stated and illustrated.

Advancing technology in the industrial field is coming to depend more and more upon precision in processing, introducing standards which would have been thought impossible a few years ago. It is true, therefore, that automatic control of industrial processes is in many cases indispensable; in others it is growing in acceptance because of the advances it makes possible in uniformity of product, reduction of production costs, and improvement in quality.

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PREFACE

This book is an introduction to the science of automatic control. In order to obtain a working knowledge of the principles of automatic control it has in the past been necessary to refer to a variety of sources. The literature on the subject is widely distributed, and, in addition, it does not completely cover the many phases of industrial process control. Analysis is restricted to more or less highly developed theories applying to particular problems. Since the appearance of Professor W. Trinks' *Governors and the Governing of Prime Movers* in 1919, instrumentation and automatic control have progressed to the development of sophisticated control mechanisms and methods without a parallel development of a generally useful foundation of theory.

The purpose of this book is to treat, in a logical manner, the important laws of operation of industrial automatic control systems and to provide a practical background of theory. Details of measuring devices and controlling mechanisms are brought out only when they are necessary to the analysis of principles and characteristics of operation. The importance of proper measurement is emphasized because of its great influence on automatic control.

Primarily, the book is intended for the student in chemical, metallurgical, mechanical, or electrical engineering. The growing importance of this subject to modern industrial processing has been acknowledged by the addition of courses in instrumentation and automatic control to the curricula of engineering colleges and technical schools. For the student, this early emphasis on automatic control is vital since a process designed and constructed with proper consideration for its control is most likely to be successful. Secondarily, the book may serve as a reference for the industrial user of automatic control equipment.

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SYMBOLS

C	CAPACITY
c	CONTROL POINT
D	DAMPING FORCE
e	BASE NATURAL LOGARITHMS
F	FLOW
f	FLOATING RATE
G	SPECIFIC GRAVITY
g	ACCELERATION DUE TO GRAVITY
h	HEAD
J	MASS
L	LAG
N	REACTION RATE
P	FINAL ELEMENT POSITION
p	PRESSURE
q	RATE TIME
R	RESISTANCE
r	RESET RATE
S	SPRING FORCE
s	PROPORTIONAL BAND
T	TEMPERATURE
t	TIME
U	TORQUE
V	VOLUME
W	ENERGY
θ	VARIABLE (TEMPERATURE, PRESSURE, FLOW, LEVEL)
π	PI = 3.1416
ϕ	PHASE OR LAG ANGLE
ω	ANGULAR VELOCITY OR PERIOD

CHAPTER 1

THE ART AND SCIENCE OF CONTROL

Automatic control, by virtue of its value to industry, is rapidly assuming importance as one of the newer sciences. It is emerging, however, from the adolescent state of an art dependent upon rule-of-thumb procedures to an exact science based on analytical methods. Fundamental laws and principles are being recognized, and as their significance becomes more widely understood scientific analysis is gradually supplanting the less reliable methods of the past.

An understanding of basic principles is of great value in the analysis of automatic control problems because these principles may be applied to any problem regardless of variations in physical or mechanical details. The control engineer can then recognize the vital factors and readily sift out the unimportant details. The automatic control problem is thereby reduced to its essential components and further analysis is simplified.

Automatic control of industrial processes is but one division of a broad and complex field which includes such diverse subjects as speed governing, temperature control, automatic airplane piloting, automatic machine operation, artillery fire control, and hundreds of other associated subjects. Industrial process control includes the control of temperature, fluid flow, pressure, liquid level, air conditioning, and any other variable quantities of an industrial process.

Electrical circuits and vibrating systems have many elementary characteristics in common with controlled processes. Characteristics similar to those of electrical capacitance, resistance, oscillatory circuits, and other electrical phenomena are found. The forced vibration of a mechanical system and the control of a process variable require almost identical analyses. Industrial process control, therefore, has many analogies in other scientific and engineering fields.

Automatic control is used for the prime purposes of efficiency and economy. It eliminates the element of human error and provides a continuous steady response in counteracting changes in the balance of the process. Automatic control pays for itself in savings of fuel, processing materials, and labor, and in the increased value of the product because of greater output or increased quality.

Automatic control must be properly applied to obtain successful results. A knowledge of application engineering in automatic control can be secured only by studying the basic laws and principles. This book is intended to serve as a guide to these fundamentals: what they are and how to use them. Many simple devices will be described, but emphasis is placed on theory rather than mechanics.

What is Automatic Control?

Automatic control* can be defined as the maintenance of a balanced state in a process by measuring one of the conditions representing the balance and providing an automatic counteraction to any change in the condition. The balance in the process may be a balance of any form of energy, very often heat or pressure.

For example, the heat balance in a water bath is maintained by measuring the temperature of the water and automatically raising or lowering the flame under the bath. As another example the flow of fluid through a pipe is held constant by measuring the rate of flow and automatically opening or closing a valve so as to oppose any change in flow.

A controlled system is so called because it consists of a process and control system. The process is the operation or function in which a

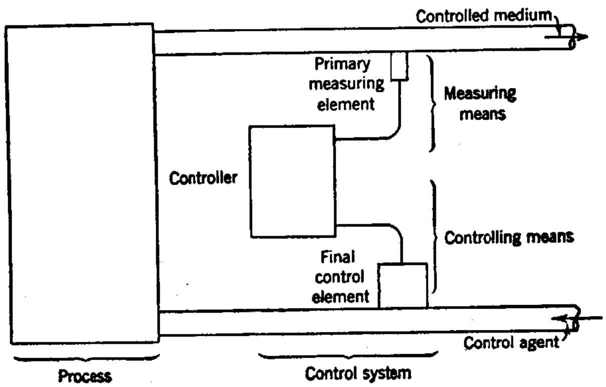

Fig. 1–1. Analysis Diagram for a Controlled System.

balance of conditions is being maintained. Figure 1–1 illustrates schematically the various components of a *controlled system.* Let us take as an example a simple water bath in which a thermometer controller maintains a constant temperature by setting the gas flow to burners under the bath.

Measurement of temperature is accomplished by a thermometer

* A glossary of the terms commonly used in automatic control is included in the Appendix.

bulb which is called a *primary measuring element.* Since the temperature of the outflowing water from the bath is measured, the *controlled medium* is the water in which a *variable* (temperature) is controlled. The primary measuring element is a part of the *measuring means* of the *controller.*

The *controlling means* consists of the controlling mechanism in the controller, such as an electric contact, and a *final control element* which may be an electric motor valve for adjusting the flow of fuel gas to the burner. The fuel gas is a medium for effecting changes in heat flow to the bath and is called a *control agent.* The control agent is always adjusted by means of the final control element.

A *control system* is made up of the measuring means and the controlling means. It generally consists of the controller and all auxiliary mechanisms used for the purpose of controlling the temperature.

The *process* is the operation of heating water to a controlled temperature. The *process equipment* is the physical apparatus, aside from the control system, used in carrying out the process operation. The *process* is the operation or function.

Measurement

The measured variable of the process is generally not an ultimate end in itself but is rather an indication representative of the state of balance of the process. For example, in measuring the temperature of a room the purpose is to measure the degree of comfort of the atmosphere. The temperature is not the only criterion, however; humidity and air motion are also important. The temperature of the room is controlled so that the balance of heat conditions is favorable for personal comfort.

Another example: the pressure in a water system is controlled to insure availability of water in all parts of the system. Pressure is the measured variable, but the controlled condition is the availability of the water supply.

Sometimes the measured variable is purely an indication of a reaction rate within a process. As an example, the outlet temperature of a thermal oil cracking unit is a measure of the rate of cracking. Pressure and other conditions are also important, however. Here, temperature is the measured variable, but the rate of cracking is the controlled condition.

Consequently, as these examples point out, it is necessary to investigate and establish the *meaning of measurement* in automatic control. The question must be continually asked, " Does the measured variable accurately represent the balance of conditions within the process?"

If a fixed, definite relation is maintained between the measured variable and the balance of the process, automatic control will generally be successful. Otherwise, the controller can only maintain the magnitude of measured variable within fixed limits without regard to the final controlled condition.

The purpose of the measuring means is to detect any change or deviation of the controlled variable. This change is then transmitted to the controller for corrective action. Naturally, one cannot expect the controller to counteract for changes which cannot be detected by the measuring means. It follows, then, that a controller is no better than its measuring means.

A change in the measured variable is not instantly detected by the measuring means of any controller. That is, all controllers indicate what the controlled variable *was*, not what it *is*. Thus, we say that the controller has measuring lag. This lag may vary from an extremely small to a very large magnitude and has a most important bearing on automatic control. We shall encounter lag again and again in automatic control, for it is present in the controlling means and process as well as in the measuring means.

Control

Automatic control is accomplished by a circle of events, beginning with a change in the controlled variable and ending ultimately with a forced return of the variable to the desired level. Meanwhile, however, the controlled variable has departed for a period of time from the desired value. Such a change in the state of balance in the process is inevitable because it is the basis for action by the controller.

Let us suppose that the temperature of a water bath is being controlled manually by setting a hand valve to regulate the flame under the bath. If the operator were watching a thermometer placed in the bath, he would open the valve when the temperature goes below the desired point and close the valve when the temperature rises above the desired point. But in order to know when to readjust the valve the operator must observe a change indicated by the thermometer. No matter how closely the operator can read the thermometer, the change in temperature has already occurred before an adjustment of the valve (a corrective action) can be made.

The action of automatic control is dynamic because of the continuous, changing character of the actions within the controlled system. Automatic control rarely achieves a steady state of balance but operates to maintain process conditions within desired limits. It is the purpose of the controller to hold to a minimum any deviation of the desired balance of the process.

The mode of control is the manner in which the controller responds to a change in the controlled variable. In the example above, the operator could have manipulated the valve in a number of ways in response to a temperature deviation. He might have closed the valve completely when the temperature was above the desired value; he might have closed the valve very slowly at a constant speed; or he might have closed the valve an additional 1 per cent for every degree rise in temperature. Other methods or combinations of methods might also have been used.

The selection of the mode of control is governed to a large extent by the closeness and quality of control desired. It is often poor economy to employ a mode capable of producing a most exacting quality of control if such quality is not required.

The final control element, such as a valve, damper, or electrical relay, is the device which actually guides the control effort — on it depends the coordination of the process and the control system. It is, therefore, a vitally important link in the control system, since the final action of the control system depends on its operation. The operating characteristic of the final element and the mode of control of the controller mechanism together make up the law of action of the control system.

Process

The process comprises an operation or series of operations to which energy is added or taken away in order to maintain a state of balance. For example, in a billet reheating furnace a balance of heat input against loss is maintained by adjusting the flow of fuel so as to compensate for the heat carried away by the reheated metal and for the heat lost by radiation, convection, stack, etc. The state of this balance is determined by measuring a furnace temperature. The process is the operation of reheating the billets.

The operation may not be a process in the chemical sense of the term. The control of fluid flow is an example. Energy in the form of static pressure head is transformed into velocity head when the fluid flows through a pipe. The state of balance is determined by measuring the pressure differential across a resistance to the flow. This simple operation is called a process in automatic-control terminology.

The controlled variable must be truly indicative of the controlled condition in the process. The controlled condition may be defined as the end purpose for which automatic control is used. The problem is to select the variable which most accurately represents the desired state of balance in the process.

In the example of the billet reheating furnace above, the purpose of applying control is to bring the metal billets into a plastic state so that they may be readily formed by rolling. The plasticity of the billets is proportional to their temperature. Since it is impracticable to measure directly the temperature of the moving billets, the air temperature in the furnace is measured and controlled. The billets must then be left in the furnace long enough to assume the proper temperature.

A process slows down or delays a change in the controlled variable caused by a change in the flow of energy to the process. This slowing down or postponement, called the process lag, is simply the characteristic reaction of dynamic changes in the process.

The lag of a process may be very large or very small. For example, the change in the flow of a liquid caused by a change in valve position in a pipe line occurs almost instantaneously, and the complete change can be made in a matter of fractions of a second. On the other hand, a change made in the temperature of a large annealing furnace by changing the flow of fuel to the furnace may require an hour or more to level out at the new value.

The process, more than any other part of the controlled system, is subject to changes from a number of sources. As many as eight or nine variables may often be found in a process, each one affecting the value of the controlled variable. The desired balance in the process cannot be maintained unless the influence of these auxiliary but related variables is kept at a minimum.

Chapter 2

MEASURING MEANS OF INDUSTRIAL CONTROLLERS

Measurement of the variable is the basis for control action since the response of the controller depends upon the detection of changes in the controlled variable. In automatic control there is always a continuous change in the controlled variable. Therefore the dynamic response of the measuring means is equally as important as its static accuracy and dead zone.

Industrial controllers may perform one of two types of service: they may measure and control without indicating the magnitude of the variable; or they may measure, indicate, and control the magnitude of the variable. In some applications there is no need for indication or recording of the variable, and non-indicating controllers are extensively used.

The measuring means of a controller has three functional elements. A primary measuring element, such as a thermometer bulb, thermocouple, or orifice, detects changes in the magnitude of the controlled variable. Transmitting means, such as capillary, wire, or piping, connect the primary measuring element to the controller. A receiving element located in the controller operates the controlling means.

A measuring means may be self-operated, that is, it may use the power developed by its own primary element for operating the controlling means, or it may be power-operated, a source of auxiliary power being utilized to amplify the lesser power of the measuring means. A pressure thermometer, for example, is generally self-operated since it employs the power developed by its receiving element for operating the controlling means. A self-balancing potentiometer is usually power-operated in that the controlling means is operated from an electric motor rather than directly from the receiving element.

It should be emphasized that the performance of any controller and its primary measuring element is largely dependent upon its installation and maintenance. Industrial controllers are precision-made equipment, and their life and performance are greatly improved by sound, well-engineered installation and thorough, methodical maintenance.

To cover in detail all the various phases of the subject of measurement and measuring devices is beyond the scope of a textbook on automatic control. The characteristics important to automatic control will be included, but for a broader study of measurement the reader should consult the references listed at the end of the chapter.

Controlled Variables

Although many conditions may require control in order to maintain the balance of the process, but few actual quantities or variables are measured and controlled.

Temperature is the most important variable to industrial processes. Nearly every process has one or more temperatures associated with its operation. Heat flow may occur in any body, and it is determined by measuring associated temperature differentials. It is not as easily directed, however, as the flow of fluids, because flow of heat does not necessarily involve physical motion of bodies.

Fluid-flow control is a means not only of proportioning the materials introduced into a process but also of supplying energy for purposes of automatic control. For example, the control of feed to a stabilizer column in an oil refinery is necessary in order to maintain the proportion of materials in the column. Another example is found in the control of temperature which may be accomplished by adjusting the flow of steam to the process.

Pressure or *vacuum* control is important in the operation of many continuous chemical processes; it is often associated with temperature conditions. For example, in handling multiple-phase liquids such as water or hydrocarbon compounds, the control of pressure is as important as the control of temperature. Another example is the control of furnace or boiler draft in metal-processing and power plants.

Liquid-level control is essential in continuous distillation processes and in many other industrial operations. Liquid level, however, is closely associated with both fluid flow and pressure. Pressure controllers are also commonly used for the control of liquid level.

Humidity control is important in air conditioning and the processing of foods and textiles. Humidity may be measured by means of dry- and wet-bulb temperatures, partial vapor pressure, evaporation, or physical expansion. Control of humidity by wet- and dry-bulb temperatures is the most common.

Other types of controlled variables in industrial processes are *p*H or acid concentration, gas analysis (CO_2, H_2, O_2, etc.), specific gravity, absolute moisture, and spectrum analysis. The controlled variables most important to industrial automatic control are, however, temperature, flow, pressure, liquid level, and humidity.

Pressure Thermometer

Thermometers of the pressure-element type utilize the thermal expansion of fluid with increase in temperature to provide an indication of the temperature. If a fluid is confined in a small containing element the expansion of the fluid with temperature raises the pressure inside the element. This pressure, which is proportional to the temperature, is measured. The pressure thermometer is usually a self-operated device.

The general construction of a pressure thermometer is shown in Fig. 2–1. A cylindrical bulb filled with a liquid or gas is subjected to the temperature to be measured. A small-diameter tube or capillary connects the bulb with the receiving element in the controller. This receiving element consists of a metallic tube which has been flattened and bent to form a bourdon tube, a helix, or a spiral. If one end of the tube is sealed and the other end fixed, a pressure increase inside the element will cause the sealed end to move in an arc. This motion is utilized to operate the control system.

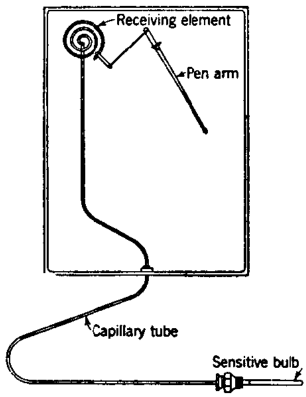

Fig. 2–1. Typical Pressure Thermometer.

The three types of pressure thermometer controllers are the liquid-expansion, the gas-expansion, and the vapor-actuated. Their difference lies in the various media for filling the thermometer system.

The *liquid-expansion* thermometer is generally filled with mercury, although other fluids such as hydrocarbons are not uncommon. Mercury expansion in a pressure thermometer results in an approximately linear relationship between temperature and movement of the receiving element in accordance with the volumetric expansion equation

$$V_1 = V_0(1 + B\theta) \qquad [2\text{–}1]$$

where V_1 = final volume.
V_0 = initial volume.
B = coefficient of volumetric expansion.
θ = temperature change.

The mercury-filled pressure thermometer is usable over a range of approximately $-35°$ to $1000°$ F.

The *gas-expansion* thermometer uses any relatively inert gas as a filling medium, nitrogen being the most common. The expansion of