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Process Control

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INSTRUMENTS PUBLISHING COMPANY
Pittsburgh 12, Penna.

Printed in the United States of America

FOREWORD

This book is designed primarily for the plant engineer, chemist or instrument engineer who wishes to install and operate process control equipment and to take full advantage of it to increase the efficiency of process operation.

In order to accomplish this, it is necessary for the plant engineer or chemist to understand the control problem, the operation of closed-loop control systems, the modes of control, the types of controller available to him, and the causes and effects of the time lag and the inherent regulation of his process and plant. This book explains the basic principles, without use of advanced mathematics, and with emphasis on the factors which are of importance in practical application. It also provides extensive coverage of commercially available controllers—pneumatic, electrical, electronic, electro-pneumatic, and mechanical—including controllers of American, British, and German manufacture.

An important feature of the book is the clarity of explanation which results from adopting the frequency-response approach, which has recently become popular in the process control field. All engineers whose responsibility includes control of chemical process operations should find that the explanations of the underlying principles of the subject and their practical application will assist materially in using available equipment and techniques to increase the productivity of their plant.

The author, A. J. Young, B.A., B.Sc., is well known in both British and American instrument circles as Head of the Central Instrument Section of Imperial Chemical Industries Limited, which has made major contributions to the application of frequency-response methods to the design of process-control systems.

Acknowledgment is due to *The Industrial Chemist* (London), in which the major portion of this book first appeared serially. Also, acknowledgment is made to Major M. F. Behar, of The Instruments Publishing Company, Pittsburgh, Pa. (U.S.A.), for contributions to the concluding chapters.

Milton H. Aronson,
Technical Editor,
Instruments and Automation

AUTHOR'S PREFACE

Two features of this book call for explanation. The first concerns the terminology employed and the second concerns the descriptions of the controllers.

The terminology is that recommended in the British Standard Glossary B.S. 1523, because the major portion of the text was written originally for the British journal *The Industrial Chemist.* If there had been a single process-control terminology in the U.S.A. at the time of writing, it would have been a simple matter to give the equivalent American and British terms each time a new term was used, but since there were several terminologies in current use in the U.S.A., it was felt that an attempt to give the American equivalent to the British terms would have led to loss of clarity in the text itself. It is thought that the use of the British terminology will present no difficulty, since the terms are to a large extent self-explanatory and are in any event defined. It will be particularly interesting at the present time to compare the clarity and ease of use of British and American terms, in view of the current efforts to frame a common terminology which combines the best features of the existing British and American standards.

The second feature requiring comment is the major contributions made by Major M. F. Behar and Mr. Milton H. Aronson, of The Instruments Publishing Company, to the chapters containing the descriptions of available control equipment. The descriptions contained in the original series of articles were included with the object of illustrating the design principles involved, and are therefore of a different nature from those contributed by Major Behar and Mr. Aronson, who have given the reader a much more self-contained and complete description in most cases. The controllers described by Major Behar and Mr. Aronson are as follows:—Askania, Bailey, Fischer & Porter, Foxboro (Model 58), Hagan, Moore Products, Republic, Taylor ("Tri-act"), Manning, Maxwell & Moore, Swartwout, Proportioneers.

The author is grateful to Major Behar and Mr. Aronson for these descriptions, which form a valuable addition to the book.

A. J. Young

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CHAPTER I

INTRODUCTION TO THE CONTROL LOOP

Automatic-control application technique has been the subject of much prolonged theoretical study. However, the theoretical basis of the technique still remains somewhat unappreciated by many plant engineers whose job it is to apply this technique to plant control problems. Consequently the design of control installations and the choice and adjustment of controllers is usually based on experience and empirical formulae.

Experience is usually a sound guide, but it takes a long time to acquire and can not be handed to a new man like a job instruction manual. Therefore, an understanding of the basic principles of any technique has two great advantages: It helps the new man to the field to do more useful work at an early stage in his career, and it enables the experienced man to make real advances in technique more readily.

Advances in technique, design and practice in chemical processes have been rapid. The choice of control equipment has become more difficult as the number of available types has increased, and the proper application to meet problems in the plant, particularly in automatic control installations, is a job for the specialist. This plant engineer or chemist needs a good, general appreciation of the fundamentals of instrumentation.

It will not be long before plants are completely designed for automatic control, and the engineer must know the plant characteristics he will have to incorporate in the control system. Unfortunately, there is not yet available sufficient data on the characteristics of existing plants (as they affect the control problem) to make such design completely possible in detail. There are, nevertheless, some well established principles to guide the designer.

Research chemists should also be kept well briefed on every improvement in any piece of plant equipment which may remove a limitation to the development of some new process. Instrumentation is constantly improving and in doing so tends to lessen such limitations; instrumentation is therefore of great interest to the research chemist. New processes have been made possible by advances in measuring and control technique.

EDUCATION

In many countries, little provision has been made for education in instrument matters in the engineering and science courses at universities and technical colleges. The U.S.A. gave the lead in remedying this state of affairs, and there is now a strong movement in many other countries to insure that engineers, physicists, and chemists are given a general grounding in the principles of modern industrial instrumentation.

An added obstacle in the way of acquiring information hitherto has been the dearth of suitable books and papers written for the "nonspecialist." This obstacle has been magnified by the wide variety of terms which have been used in discussions and papers on automatic control. There now is progress toward an international terminology; this time the lead comes from Britain. The British Standards Institution has now issued recommendations for a standard terminology. The terminology recommended by the American Society of Mechanical Engineers, which is basically similar to the B.S.I. terminology, will be presented for comparison.

COLLABORATION BETWEEN MAKERS AND USERS OF INSTRUMENTS

Many instrument manufacturers have strong teams of development and application engineers, but without a strong "feedback" of plant experience from the users, the manufacturers are needlessly hampered in producing the best possible equipment. It is salutory to recall, in this connection, the history of the development of the now familiar automatic potentiometer recorder.

The first models were designed and built before 1895 by Professor H. C. Callendar at Cambridge in collaboration with Sir Horace Darwin, founder of the Cambridge Instrument Company, for the measurement of temperatures in blast furnaces. As British industry did not realise the importance of this development, the development was perfected in the U.S.A. Thus the idea which originated at Cambridge, England, was later exported in fully developed form to England from the U.S.A.

In a similar manner the work on automatic control by Callendar, Hartree and Porter received very little attention until it was used in the United States for developing control theory for application to pressing plant problems.

Such neglect of brilliant research work cannot occur when plant managers know and appreciate what a valuable tool instrumentation is; it is the duty of "specialists" to keep their non-specialist colleagues in the plant and laboratory well informed.

APPLICATION FACTORS AND ADVANTAGES

Control, whether manual or automatic, cannot be more accurate than the measurements of the controlled condition upon which it is carried out. Discussion of the measuring system is outside the scope of these articles, but the important general requirements will be stated as seems necessary for giving a picture of the control problem as a whole.

Automatic control does not replace operators. It helps operators to achieve better control, and to obtain maximum plant efficiency with less effort and with greater consistency.

In the complex plant, which depends on the close interrelation of many variables, manual control is often impossible. Such plants have only come into being because of automatic control.

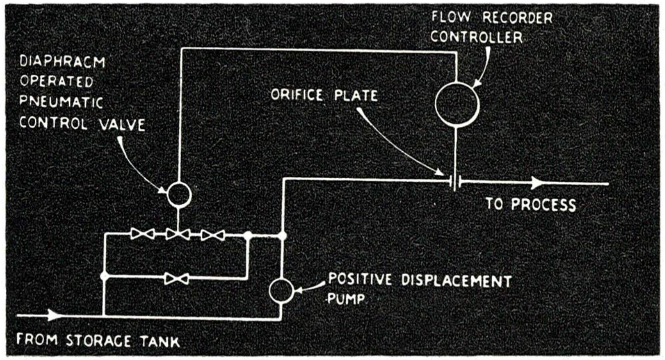

Fig. 1. Flow-control system with control valve in parallel with pump; series connection is not used because pump might be damaged if controller shuts off valve in series with pump.

Large reduction in operating costs result from even a small percentage reduction in reject product, or in lost production time. Advantages of automatic control include also the improvement in working conditions that result from the smooth and safe running which can be assured by automatic control. The savings in capital and running costs which would result from designing plants specifically for automatic control are now being investigated.

TERMINOLOGY

The automatic-control-system closed loop. Every automatic control system forms a complete closed loop of which the plant is an integral part. Such a loop is shown diagramatically in Fig. 1 for a flow-control system, and in Fig. 2 for a temperature-control system. Both systems are of the general form shown in Fig. 3, of which the component parts are:

(i) A *measuring unit* which gives the measurement of the controlled condition (temperature, flow, liquid level, pH, conductivity, refractive index, absorption coefficient for a given kind of radiation, or any other variable upon which the process can be controlled).

(ii) A *controlling unit* designed to (1) compare the measured value of the controlled condition with the value of the controlled condition which it is desired to maintain (i.e., the *desired value* of the controlled condition) and (2) to take the necessary action to decrease the difference between the two values (i.e., the *deviation*) to a minimum.

(iii) A *regulating unit,* which may be a rheostat in an electric circuit, a valve in a pipeline, a variable-speed gear on a machine, etc. The controller operates the regulating unit to maintain the controlled condition as close as possible to the "desired value."

(iv) *The plant.* The system is completed by the plant, and the difficulty of the control problem depends on the location of the point of measurement of the controlled condition relative to (1) the location of the regulating unit and (2) the point at which disturbances enter the plant.

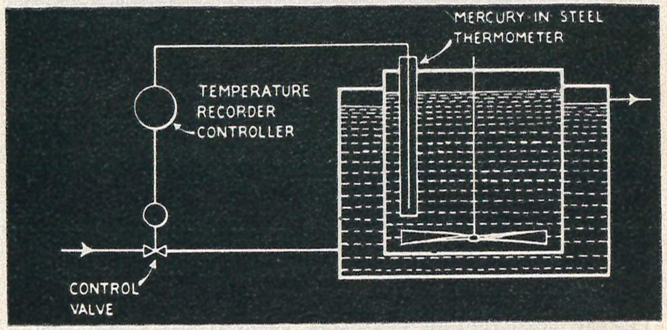

Fig. 2. Temperature-control system for a batch process. Hot water enters at left an leaves at right to maintain chemical solution in inner tank at desired temperature.

British Standards Institution recommended terminology. The terms used in describing the control loop are those recommended by the British Standards Institution, as quoted from the B.S.I. "Glossary of terms used in Automatic Controlling and Regulating Systems—Section II—Process Control." The number given with each definition is the reference number of the term in the glossary.

2102. *Controlled condition.* The physical quantity or condition of the plant which it is the purpose of the system to control.

2103. *Desired value (index value).* The value of the controlled condition to which the automatic control mechanism is adjusted. In process control the desired value may be fixed or it may be varied by an external agent.

2104. *Signal.* The physical quantity by which one part of the control system influences another.

2105. *Automatic controller.* A mechanism in which the value of a controlled condition is compared with a desired value and which operates in such a way as to reduce the deviation of imposing control action on a regulating unit. It comprises the measuring element and the controlling unit.

2106. *Measuring unit.* The unit comprising those elements (detecting element and measuring element) that ascertain the value of the controlled condition.

2107. *Detecting element.* That part of the measuring unit that responds directly to the value of the controlled condition.

The terms "detecting element and "measuring element" should not be confused. The former is the "pickup," the latter is the measuring instrument exclusive of the pickup, or detecting element.

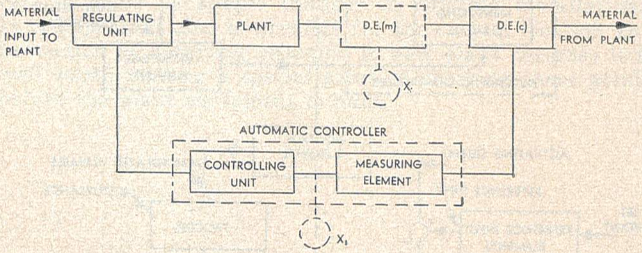

Fig. 3. Automatic-control-system closed loop. D.E. (c) is detecting element of automatic controller. Dotted lines show alternate positions for monitoring indicator or recorder. D.E. (m) is detecting element for monitor.

"Indicator" or "recorder" is not used for the measuring element because many systems do not have an indicator or recorder in the closed-loop control cycle.

The detecting element and measuring element are treated separately so that the characteristics of each can be considered. In addition, the measuring element and controlling unit can be treated as one unit called the *automatic controller.*

A number of automatic controllers are used with no provision for indication or recording of the controlled condition, but the general practice has been to use a recorder as the basis of the control system. In such systems the recorder is an integral part of the controller because the same mechanism provides motive power for both the controlling unit and the recording pen. However, the advent of new all-electric systems is emphasizing the merits of obtaining a record, either for monitoring or accountancy purposes, by a separate recording unit. This unit may be in parallel with the control loop, as at X_1 in Fig. 3, or it may be connected to a separate detecting element, as at X. The latter arrangement gives a completely independent and more reliable check on the operation of the control system.

Terminology of the American Society of Mechanical Engineers. The A.S.M.E. has recommended a terminology based upon the units shown in Fig. 4, which compares the B.S.I. and A.S.M.E. systems and reveals the basic similarities.

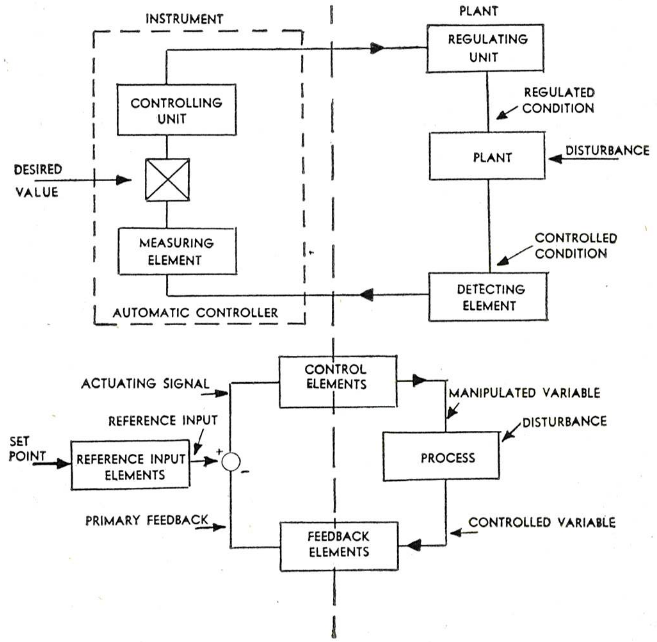

Fig. 4. Comparison of B.S.I. (top) and A.S.M.E. (bottom) control-loop diagrams.

CHARACTERISTICS OF THE DETECTING ELEMENT

The characteristics required of an automatic controller for any given application depends upon the characteristics of the plant, the detecting element, and the regulating unit to be employed.

The detecting element and regulating unit selected for a control system depend upon the condition to be controlled. In a chemical works this is usually either temperature, fluid

flow, pressure, liquid level, or composition of raw material, intermediate product, or final product. It may also be a physical dimension such as thickness, speed of a machine, or color. But whatever the controlled condition is, it must be measured accurately and quickly so that the controlling unit can take action to nullify any departure from the desired value.

It is therefore vital to the automatic control system that the right choice of detecting element is made for any given application, and that the element selected is installed in the best manner. It is always necessary to make a compromise between the ideal installation from the measuring point of view, and the robust, corrosion- and vibration-proof installation which gives no maintenance troubles. It is impossible to choose the element, its location, and its protection from damage, unless the underlying principles governing its response are thoroughly understood. Therefore, the next article in this series will discuss these principles and their application in practice. The fundamental considerations are not of academic interest only; surprising improvements in control accuracy and speed of response often can be made by simple changes in existing installations. It is important also to arrange for the correct location and protection of detecting elements in new plant designs; it is well worth making a special point of checking these points before the plant equipment is built.

CHAPTER II

RESPONSE OF DETECTING ELEMENTS

Time lag occurs between a change in plant conditions and the receipt of a warning of this change by the operator or by the controlling unit. This time lag is due to the finite time required for the following actions to take place: (i) The detecting element to come to equilibrium with the new value of the measured condition; (ii) transmission of the signal from the detecting element to the measuring element; and (iii) the measuring element itself to measure the signal and either to indicate its value to the operator or to pass it on to the controlling unit.

Almost always, in any measuring system, one of the three sources of lag is much more important than the other two. In attempting to minimize lag, this source should be considered first and all possible steps taken to reduce its effect. For example, in temperature measurement, lag (i) is usually the greatest. In pneumatic transmission, lag (ii) can be greatest. In flow measurement with an orifice and manometer, lag (iii) can be greatest.

In this article we shall be concerned solely with (i), the time lag of the detecting element.

Any time lag in measurement implies a measuring *error* whenever the measured condition is changing. The detecting element supplies the measurement not only late but also inaccurately, except in steady conditions. The "slower" a detecting element is, the less chance it has of attaining equilibrium with a continuously changing measured condition. A large disturbance may not be shown up at all if it is of sufficiently short duration compared to the measuring lag. This explains many a steady record which has been produced as evidence of steady control, when, in fact, the plant has been suffering consistently from short-period disturbances.

Of the most common measurements in the plant, namely temperature, pressure, flow and level, temperature measurement suffers most from time lag and presents the most difficult problems in eliminating it. The following discussion is therefore mainly concerned with the lag in temperature detecting elements. Some general remarks of practical interest on lag in other detecting elements will be made in a later article. The same general theory, however, applies to them all.

Apart from the three sources of lag in the measuring unit, which were given at the beginning of this section, there are three more sources in the complete control loop, namely: (1) Lag in the controlling unit; (2) lag in transmission of the controlling unit signal to the regulating unit and in the response of the latter; and (3) lags in the plant between corrective action at the regulating unit and response at the detecting element. ("Distance-velocity" and "transfer" lags).

DEFINITION OF "MEASURING LAG" FOR A DETECTING ELEMENT

The rate at which a bare temperature-detecting element changes temperature in response to a change in the temperature of its surroundings depends on: (1) The thermal capacity (C) of the element and (2) the rate at which heat is exchanged between the element and its surroundings. This rate depends on (a) the resistance to the flow of heat (R) across the boundary between the element and the fluid surrounding it, and (b) the difference in temperature between the element and the fluid.

Note that the thermal capacity of the element is a property of the element itself. The resistance to heat flow, however, depends on the nature of the fluid and the speed at which it flows over the element. The resistance of the boundary layer increases as the thermal conductivity, specific heat, and density of the fluid increases, and decreases as its viscosity increases. As the resistance for a gas is 50 or 100 times higher than for a liquid with the same speed past the element, it is more difficult to obtain rapid response in measuring the temperature of a gas.

We can define the measuring lag in terms of C and R, as defined above.

Case 1. *Temperature-detecting elements subjected to sudden change in temperature of surrounding fluid.*

If a temperature-detecting element is suddenly plunged into a fluid at a higher temperature, the *rate* at which it commences to rise to the new temperature will be proportional to the initial temperature difference and to $1/CR$. We can therefore regard CR as a constant. As the temperature difference decreases, the rate of rise of temperature of the element decreases proportionately until it finally becomes infinitely small. The response curve therefore will be of the shape shown in Fig. 2-1 for a bare thermocouple, which is an exponential curve.*

Measuring lag often is defined and experimentally determined as the time which elapses before the initial tempera-

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*Since all detecting elements have both distributed resistance and capacity, they do not follow the exponential law exactly—but the error involved is not appreciable for our present purpose. For a detailed discussion of this point see M. F. Behar, *Instruments,* Aug. 1948, pages 691-698.

ture difference between the element and the measured condition is reduced by a fixed percentage. Any arbitrary percentage could be used, but it is usual to take (in round figures) 63 per cent. This percentage is taken because in a time interval (T) of RC seconds, the exponential passes through 1-1/e, or 63.2 percent, of its final amplitude change.

This "step change" approach is not discussed further because sudden changes in conditions are in general neither desirable nor easy to produce in a plant. Therefore lag will now be discussed and defined in terms of a continuously changing measured condition.

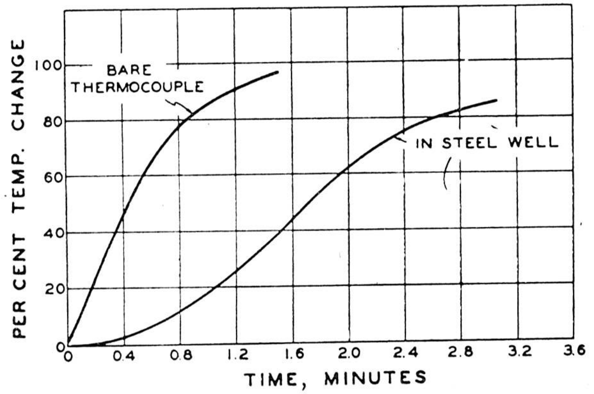


Fig. 2-1. Response of (a) bare element and (b) element in well to sudden, sustained change in ambient temperature. Note delayed start of curve at right.

Case 2. *Temperature-detecting elements subject to constant rate of change in temperature of surroundings.*

If the plant fluid temperature is increased at a constant rate, the response of the temperature-detecting element will be as shown in Fig. 2-2. After sufficient time has elapsed, the indicated temperature will lag behind the actual temperature of the fluid by a constant amount. The distance between the two parallel lines on the time axis in Fig. 2-2 is the measuring lag (T), and $T = CR$. (See appendix). If the indicated temperature lags behind the actual temperature by θ degrees, the heat absorbed by the element must be $\theta \times C$. But the temperature difference is constant at θ, and rate of heat flow to element is therefore θ/R. Hence

$$(\theta/R)\ T = \theta C$$
$$T = RC.$$

This method of determining T is flexible for both laboratory and plant use. It has the advantage that measurements are taken over a period so that erratic disturbances can be averaged out by drawing the parallel straight lines through the points determined experimentally.

Case 3. *Temperature-detecting element subject to a disturbance varying continuously in sine wave form.*

The output of the element is measured and is also of sine wave form (Fig 2-3). However, (a) the detecting element never reaches the maximum or minimum temperatures to which it is exposed, (b) the maximum and minimum points on its own response curve lag behind those of the impressed disturbance, (c) as the measuring lag T becomes larger, the response has smaller amplitude and the lag of response increases, and (d) as the frequency (n) of the impressed disturbance is increased, the attenuation and lag of response signal become greater. The formulae for element lag (L) in terms of signal attenuation and phase lag are given in the appendix.

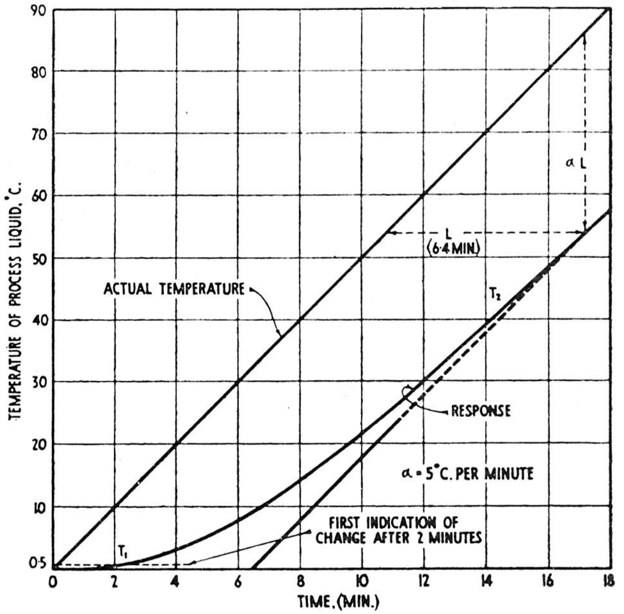


Fig. 2-2. Response of element in well to constant rate of change of process temperature. (Element used is shown in Fig. 2-4.)

Plant engineers will appreciate that the lag measurement can easily be made in this way on the plant itself, by setting the controller to produce steady "hunting". By recording the temperature as measured by the element under investigation and also by a special element with negligible lag, the curves of Fig. 2-3 can be produced and compared.

It is suggested that the most reliable way of finding L for an actual plant installation is this method. If not practical, the "continuous rate of temperature increase" (Case 2) should be used.

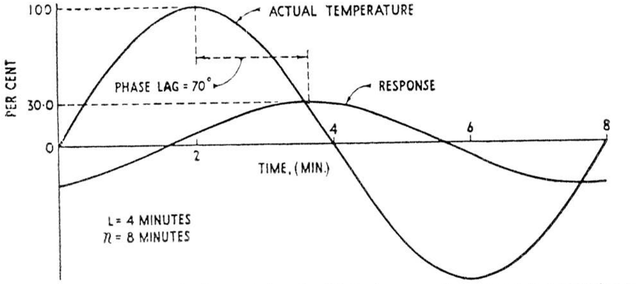


Fig. 2-3. Response of element to sinoidal change of process temperature, showing attenuation and phase lag.

Detecting Element in Protective Well

When the element is housed in a protective well, the rate of transfer of heat to the element from the plant fluid is decreased because of (i) well wall resistance; (ii) resistance of air or filling medium between element and pocket; and (iii) resistance of any dirt layer which generally collects on the well in plant conditions.

In addition, the well introduces more material to be heated to the final temperature. This additional thermal capacity increases the measuring lag further.

Finally, additional heat will be lost by conduction along the well wall to the pipe wall and atmosphere. This heat loss has the same effect as an increase in thermal resistance because it effectively decreases the rate of heat flow to the element.

Thus the well is responsible for the major part of the measuring lag in most temperature installations. It is worth while to consider the relative orders of magnitude of the contribution of each component of the installation to the total measuring lag by taking a specific example.

Example of Element-in-well Response

The following example refers to an existing installation in a chemical plant. The well (Fig. 2-4) is about 10-ft. long (in a vat used for a batch process); therefore losses by conduction along the well to the external atmosphere need not be considered in this instance.

As shown in Fig. 2-4 the heat transfer takes place through the resistances R_F, R_p *and* R_f (fluid film, well wall and filling liquid respectively) before it reaches the element. The thermal capacities which account for delays are (C_p) well wall capacity, (C_f) filling liquid capacity, and (C_E) element capacity.

An approximate expression for the time lag L is:

$$L = C_E R_f + (C_E + C_p)(R_F)$$

and the response curve is shown in Fig. 2-2 for a steady rise in process material temperature.

In this equation, note that there are two ($C \times R$) terms or time constants. These make the element slow at the beginning of any change.

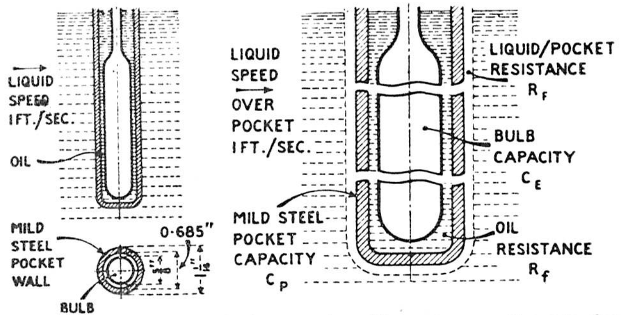


Fig. 2-4. Mercury-in-steel thermometer. Thermal properties are shown at the right.

It is important to note how this shape affects control: (1) The controlling unit will first know corrective action is necessary, and in which direction, at time T_1 *after* the change has commenced, where T_1 is the time at which the measuring unit is just able to detect the signal from the detecting element. This may be several minutes after the change has commenced. (2) The shape of the curve at the beginning of the disturbance gives no information to the controlling unit on the magnitude of the change or rate of change of the process controlled condition. A human operator can rely on experience to know how much corrective action to take—and he may be wrong. The automatic controller can only wait for more information. It is clear that it is essential to reduce measuring lags to a minimum if best control is required. These conditions also emphasize the importance of the product (sensitivity × speed of response) for the measuring element.

In the expression for time lag, the thermal capacities and resistances of the metal parts are known. This is not true for (a) the air gap (or filling liquid) between the well wall and element, (b) the dirt film on the outside of the wall, and (c) the boundary layer between the wall and the surrounding fluid.

Experience based on experiment, or tabulated information compiled by someone else who has done experiments in similar conditions, is the only safe way to estimate (a) and (b). Item (c) becomes very small if the speed of the liquid past the well is kept high, above (say) 1 ft. per second. For gas the speed over the well should be 10 ft. per second or more. It is important to *either arrange for a close fit between bulb and well* or *fill the space with a good conductor* (oil or mercury). Also, keep the well surface clean, and decrease the liquid/wall boundary resistance to a minimum by keeping the fluid speed past the bulb high.

For the bulb shown in Fig. 2-4 let us consider what happens per unit length of the bulb. Oil is used as a conducting medium between wall and bulb.

The bulb itself and the mild-steel well can be considered as primarily thermal capacities (C_E and C_P); the liquid/pocket boundary and the filling oil primarily as thermal resistances (R_F *and* R_f). Then, per unit length, and in c.g.s. units:

C_E = mass/unit length × sp. heat = 1.3

C_P = mass/unit length × sp. heat = 2.48

R_F = 0.67 (by experiment, for a liquid speed of 100 ft./minute)

R_f = thickness of oil gap/(π) (mean dia. of gap) × (oil conductivity)

$R_f = 125$

Substituting these values in the equation for L:

$$L = 1.3 \times 125 + (1.3 + 2.48)\ 0.67 = 165 \text{ sec.}$$

Note that R_f is the outstandingly high factor contributing to L. There is little point in reducing any of the others until the resistance of the oil layer is decreased. This can be done by fitting a new well to give a clearance of 0.01 instead of 0.08 inch between well and bulb. This brings R_f down to say 15. We then have:

$$L = 1.3 \times 15 + 3.78 \times 0.67 = 22 \text{ sec.}$$

instead of 165 sec.

If unavoidable lag is brought about by an anti-corrosion lead covering on the well, it would be necessary to reduce ($C_E + C_P$). As the element capacity has been made small by the makers, the only possibility would be to reduce the capacity of the well, if a lighter construction would be safe.

SUMMARY OF FACTORS MAKING FOR QUICK RESPONSE

When quick response of a thermometer element is essential (and it is always desirable) the following should be aimed at: (1) A close fitting bulb and well. (2) An oil filling (or mercury when conditions permit) in the gap. (3) A high speed (100-ft. per min.) of liquid over the well to keep a clean external surface of the well and to reduce the fluid/surface resistance to a minimum. (For gases the speed should be 500-ft. per min.). (4) The lightest-weight well compatible with plant conditions. (5) The deepest possible immersion of well, especially in small pipelines. If these factors are attended to, the manufacturers can be relied on to supply a sufficiently low-lag element.

APPENDIX

Let us then consider the response of an element of long cylindrical shape (like a mercury in steel element) as shown in Fig. 2. The rate at which its temperature (θ_E) rises, when the surrounding fluid is at temperature θ_F, depends on the amount of heat ΔQ which flows into unit length of the element in a small time ΔT. The temperature change ($\Delta\theta_E$) of the element in this time interval will be given by :—

$$\Delta\theta_E = \frac{\Delta Q}{C_E}$$

where C_E = thermal capacity of the element/unit length.

Now $\Delta Q = \dfrac{\theta_F - \theta_E}{R_F}\ \Delta T$

where R_F = resistance to heat flow from the liquid to unit length of element.

∴ the rate of rise of temperature of the element

$$= \frac{\Delta\theta_E}{\Delta T} = \frac{\Delta Q}{\Delta T . C_E} = \frac{\theta_F - \theta_E}{R_F . C_E}$$

$$i.e.,\ \theta_E = -\,C_E . R_F \frac{d\theta_E}{dT} + \theta_F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

A solution of the differential equation (1) is :—

$$\theta_E - \theta_F = (\theta_E{}^\circ - \theta_F{}^\circ) e^{-\frac{T}{C_E . R_F}} - e^{-\frac{T}{C_E . R_F}} \int_0^T \frac{d\,\theta_F}{dT} . e^{\frac{T}{C_E . R_F}}\, dT \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $\theta_F{}^\circ$, $\theta_E{}^\circ$ are the initial temperatures of fluid and element and θ_F, θ_E are corresponding values at time T.

(The step from eq. (1) to eq. (2) must be accepted as a mathematical fact.)

Eq. (2) enables us to predict the lag in response of the bare element under consideration for the three conditions mentioned above, namely :—

(1) θ_F constant = $\theta_F{}^\circ$.

This corresponds to the condition in which the element is plunged into a fluid at a different temperature (θ_F°).

(2) θ_F varying at a constant rate, and

(3) θ_F varying sinusoidally.

$\frac{d\,\theta_F}{dT}$ is the rate of change of θ_F, so that we have :—

Case (1) $\frac{d\,\theta_F}{d\,T} = 0$ (since θ_F is constant),

Case (2) $\frac{d\,\theta_F}{d\,T} =$ a constant $=$ (say), α, and

Case (3) $\theta_F = \theta_F^\circ + A \cos \omega\, T$

where $A =$ amplitude of the temperature oscillation

and $\frac{2\pi}{\omega} =$ period of oscillation,

giving $\frac{d\,\theta_F}{dT} = \frac{d}{dT}\,(A \cos \omega\, T) = -\,A\,\omega \sin \omega T.$

We can now substitute in eq. (2) for the three cases

Case 1.— $\theta_F - \theta_E = (\theta_F^\circ - \theta_E^\circ)e^{-\frac{T}{C_E R_F}}$ .. ...(3)

If $T = C_E\, R_F$ then :—

$\theta_F - \theta_E = (\theta_F^\circ - \theta_E^\circ)e^{-1} = 0{\cdot}368\ (\theta_F^\circ - \theta_E^\circ)$*

Thus after a time T such that $T = C_E\, R_F$, the temperature difference between element and fluid will have been reduced by 63·2 per cent.

Note: $C_E\, R_F$ has the dimensions of time and is known as the time constant of the system. From what follows it will be seen that it is equal to the *time lag* for a linear rate of increase of the fluid surrounding the element.

Case 2.—Putting $\frac{d\,\theta_F}{dT} = \alpha$, we can obtain from equation (2) :

$$\theta_E - \theta_F = -\alpha(C_E\, R_F) + (\theta_E - \theta_F + \alpha\, C_E R_F)e^{-\frac{T}{C_E . R_F}} \quad \ldots(4)$$

The last term decreases as T increases, so that after a suitable time we have the steady condition :—

$$\theta_F - \theta_E = \alpha\, C_E\, R_F$$

Fig. 3 shows values of θ_E and θ_F taken from equation (4) plotted against time (T). It is clear that the *measuring* lag is $\theta_F - \theta_E$ which we have just seen is equal to $\alpha . C_E . R_F$. It follows from the figure that the *time* lag (L) is $C_E R_F$.

The point of interest is that in these conditions the lag L is always equal to $C_E\, R_F$ whatever the rate of rise of temperature. We can therefore define the time lag in a very commonsense way as the time which elapses between θ_F and θ_E reaching the same temperature say θ, when θ_F is increasing at constant rate and conditions have become steady.

It is useful to note that the temperature of the element θ_E at any time differs from the true temperature of the fluid θ_F by an amount $= \alpha \times L$.

Case 3.—If($-A\,\omega \sin \omega\, t$) is substituted in equation (4) for $\frac{d\,\theta}{dF}$ and the differential equation is solved for θ_E, then it will be found that θ_F and θ_E follow the temperature/time curves shown in Fig. 4. It will be seen that θ_E lags behind θ_F and also that the amplitude of variation of θ_E is smaller than that of θ_F.

The actual percentage reduction in amplitude is found to be :—

$$\frac{100}{\sqrt{1 + (L\omega)^2}} \quad \text{or} \quad \frac{100}{\sqrt{1 + \left(2\pi \frac{L}{n}\right)^2}}$$

where $L =$ time lag of detecting element and $n =$ period of the process disturbance.

Hence if $L = 4$ min. and the plant is " hunting " with a period of 8 minutes, the amplitude of measured temperature will be only 30 per cent. of that of the actual temperature variation.

The additional difficulty of controlling the process when only 30 per cent. of the temperature change is measured is obvious.

There is, however, another very important reason why the detecting element lag increases the difficulty of control. In Fig. 4 it will be seen that the detecting element signal lags behind the disturbance to the measured condition.

The plot of the detecting element signal is therefore also a sine wave, but both smaller in amplitude and displaced along the time axis. This displacement can be described as a phase lag (ϕ) and its value can be derived from equation (4) as :—

$$\phi = \tan^{-1} \frac{2\pi\, L}{n} \text{ radians.}$$

CHAPTER III

THE CONTROL PROBLEM

In any given plant, satisfactory control depends on the following factors:

(1) The ease or difficulty of making sufficiently consistent measurements of the controlled conditions with the required speed, sensitivity and sensitiveness.

(2) The lags in the plant (and in the controller), and the capacity of the plant for absorbing energy and so tending to slow down changes in the controlled conditions.

(3) The closeness of the limits between which the controlled conditions must be maintained.

(4) The amount of energy absorbed or evolved in the process reactions and its relation to the values of the controlled conditions.

(5) The nature of the process materials (and their temperature and pressure) as it determines the materials selected for those parts of the regulating units and detecting elements which come into contact with them.

(6) The number of variables affecting the process, and the amount and nature of their variation.

Present practice on chemical plants is, in most instances, to control each variable separately (such as the feed rate, pressure, and temperature of ingoing materials in a continuous process) and also to control the reaction itself on the temperature or pressure in the reaction vessel (or less frequently on some physical property of the product which determines its quality). At first sight it would appear that if the conditions are carefully controlled the final control of the reaction itself ought to be unnecessary. However, it is not possible to control the conditions perfectly, nor is it possible to control changes (such as a decrease of catalyst activity in a converter or of the heat transfer coefficient in a heat exchanger) which are continually taking place in the plant itself. No one who has been responsible for running a chemical process of any complexity will question the need for this final control after steps have been taken to create constant conditions by controllers installed on the supply side.

The total control problem can be broken down into a number of individual problems, in themselves more or less difficult to deal with according to the nature of factors (1) to (5) in each case. We shall, therefore, confine our discussion to the individual control loop and, by examining the demands made on the controller as factors (1) to (5) assume different degrees of importance, we shall show the need for the major types of control action employed.

Considering factor (1), the controlled condition cannot be maintained constant within limits narrower than those within which it is measured. The effect of speed and sensitiveness of measurement on the control system was discussed in Chapter 2. The lag in the measuring system will, in the following discussion, be considered as a part of the plant lag as far as the controller is concerned. Bearing this in mind, we can now consider factor (2).

Lags in the Plant

In addition to the measuring lag, there will in general be two other types of lag in the plant—*distance-velocity lag* and *transfer lag*.

Distance-velocity lag is simply the DELAY which occurs between the injection of a change in condition (say temperature or pH) of a plant material (generally a fluid) and the time at which this disturbance arrives at the detecting element. For example, if a liquid is heated by heater H in Fig. 3-1, the detecting element receives information of any change in heat input at a time *after* the heat input changes. This time lag is d/v, where d is the distance separating heater and detecting element, and v is the velocity of the fluid. Hence this time is called distance-velocity lag. Note that d/v is a time measured in units of time.

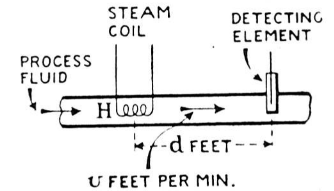


Fig. 3-1. Heating system showing origin of distance-velocity lag.

The B.S.I. definition (2302) of distance-velocity lag is: The time interval between an alteration in the value of a signal and its manifestation unchanged at a later stage, arising solely from the finite speed of propogation of the signal.

The A. S. M. E. defines distance-velocity lag as *dead time*. Another term used is *transportation lag*. The A.S.M.E. definition (204) for dead time is: Any definite delay between two related actions; measured in units of time.

Note that a true distance-velocity lag does not change the magnitude of the disturbance between input and detecting element. For example, if the pipe of Fig. 3-1 is perfectly insulated no heat is lost by the fluid in distance d and the temperature change remains at its initial value all the way along the pipe. In practice, however, a change nearly always occurs because of heat loss, etc.

Transfer lag is that part of the transmission characteristic, exclusive of distance-velocity lag, which modifies the time-amplitude relationship of a signal and thus delays the full manifestation of its influence (B.S.I. Definition 2303). It is caused by the effective resistance and capacitance of the various elements in the system.

The lag of a detecting element (Chapter 2) was seen to result from the combined effect of the resistance to heat transfer from process material to detecting element and of the thermal capacity of the element and its protective pocket. Thus it is a transfer lag and is of exactly the same nature as the transfer lags which occur in the plant between a source of heat and a process material or between the two sides of a heat exchanger.

For example, a comparison of Fig. 3-2 and Fig. 2-4 shows that the transfer lag in a batch-heating process is exactly analogous to the thermometer in a sheath. Hence if the dimensions and materials of construction of the vessel are known, the transfer lag can be calculated in the same way as was employed for the detecting element.

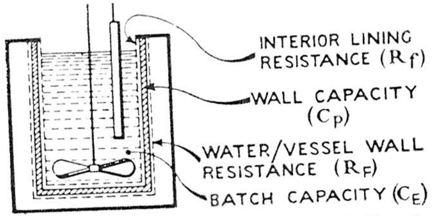


Fig. 3-2. A batch-heating process, illustrating transfer lag.

Distance-velocity lags produce no change in magnitude of the input disturbance, but only a delay before the effect is shown. Transfer lags produce both amplitude and phase changes.

If the disturbance is a sine wave of period T; both types of lag result in a phase lag between the original disturbance and its appearance at the detecting element. If the lag (time between maximum point of disturbance and maximum response of detecting element) is L, then the phase lag caused by distance-velocity lag is $2\pi(L/T)$ radians; and the phase lag caused by transfer lag is $\tan^{-1} 2\pi(L/T)$ radians.

Distance-velocity lag does not decrease the magnitude of the disturbance before it reaches the detecting element; however, the transfer lag decreases the disturbance in the ratio:

$$1: \sqrt{1+(2\pi L/T)^2}.$$

Note that this formula is the same as for the thermometer in a well (Chapter 2). Note also that as T increases, the ratio becomes closer to unity. The easiest way of examining the effects of lags is to consider the form of control most easily understood.

TWO-STEP ACTION

The term "two-step" controller action now is used instead of "on-off" or "open and shut" action. The B.S.I. definition (2408) of two-step action is: A control action in which two predetermined control actions are alternated at a chosen value of the controlled condition."

The A.S.M.E. calls this action *two-position* action and defines it as: Two-position action is that in which a final control element is moved from one of two fixed positions to the other (definition 501a).

Two-step action is thus given by a controller which sets the regulating unit at one of two positions according to the process requirements. Note that this term does not imply that one setting necessarily represents "regulator shut" and the other "regulator full open." The term suggests two different settings of the regulator, and is a great improvement on the old term "on-off action" which did suggest (and originally did mean) that the controller either opened the regulator fully or shut it completely. A great deal of unnecessary trouble has been caused in industrial plants because two-step action has been interpreted in this restricted sense and has been applied accordingly.

Suggestions that two-step control action might be used much more with advantage are not always taken seriously by those accustomed to dealing with the more complex methods which will be discussed later. There are, however, a great number of applications in which two-step control will give satisfactory results at low initial cost. It is fairly safe to predict that progress in the study of plant characteristics, coupled with the possibility of decreased measuring lags and greater sensitiveness of measuring units, will increase the use of this form of control. Certainly such progress will increase the tendency to employ the next simplest type of control, namely narrow-band proportional control. In view of the general lack of appreciation of the simple considerations involved in applying "two-step control action," it is useful to discuss them. First, let us consider an ideal case and, by noting how practical cases depart from it, derive some working rules for application on the plant.

Level Control by Two-step Action

The purpose of controlling level is normally (1) to prevent a tank overflowing or emptying, (2) to maintain a constant head of liquid in the tank to supply a constant rate of flow of liquid to a process—that is, for indirect control of flow by level control, or (3) to keep the level in a tank or vessel between limits when the vessel is used as a surge vessel—that is, to smooth out disturbances in the flow to a process.

The regulator in case (1) can be in the output or input pipe, but to meet the requirement of (2) and (3) it usually is in the input when two-step action is employed. Consider the level-control system shown in Fig. 3-3 when its function is to control the level *LL* to within $\pm l$ inches, when the outflow from the tank is (1) constant and (2) varying.

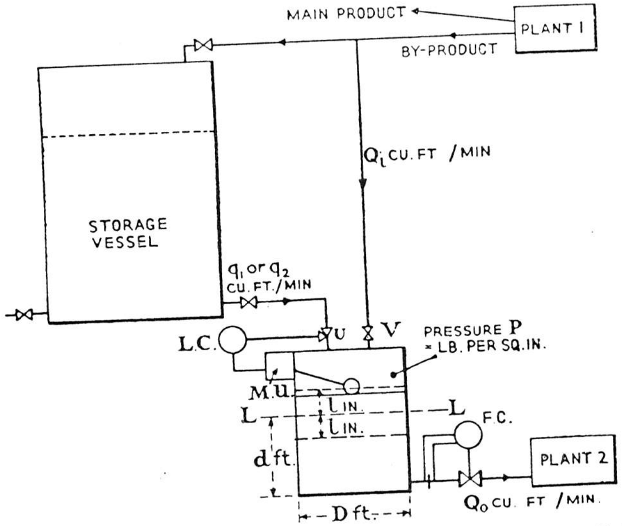


Fig. 3-3. Level control system in which level LL is to be controlled.

Case (1)—*Outflow Constant.* This condition will exist in a plant in which a feed of starting material is received from another process. This earlier process may yield the material as a by-product and at a varying rate depending on demand for the main product. There must therefore be some capacity between the two plants to absorb these variations.

Plant 2 (Fig. 3-3) will receive a constant flow Q_o, controlled by the flow controller (F.C.) as long as there is some liquid in the storage vessel. The first requirement of the level controller is therefore to ensure that the vessel never empties nor becomes completely full. This can be ensured by setting the main supply valve (*V*) so that it delivers at a rate (Q_i cu.ft. per min.) always somewhat less than the constant supply to Plant 2 (Q_o cu.ft./min.), and arranging for the difference ($Q_o - Q_i$) to be made up from the storage vessel through valve *v*.

Remembering that two-step control means that the level controller can give valve *v* only two settings (equivalent to q_1 or q_2 cu.ft. per min.) we can now examine the operation of the controller. The expected fluctuations in Q_i are such that $Q_i + q_1 < Q_o < Q_i + q_2$.

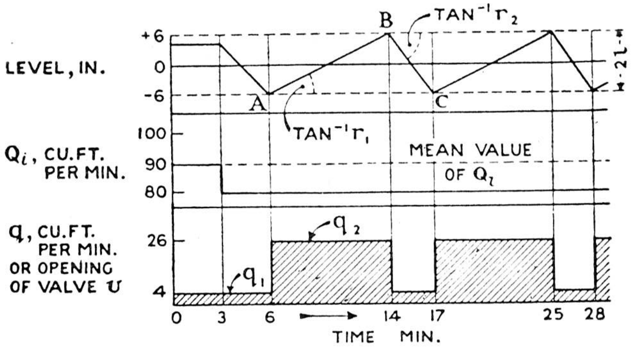


Fig. 3-4. Response of system in Fig. 3-3.

Then if R = radius of vessel (ft.) and the level is falling, immediately the level has fallen the preset amount (l in.) below the desired level (*LL*) the controller sets valve *v* to give q_2 cu. ft. per min. Assuming that Q_i remains constant during the next few minutes, the rate of rise of level will be:

$$r_1 = 12\ (Q_i + q_2 - Q_o)\,/\,(\pi R^2) \text{ in. per min.}$$

The time for the level to reach the high-level limit is

$$t_1 = 2l/r \text{ minutes.}$$

When the high level is reached, the controller changes the setting of valve *v* to give q_1 cu. ft. per min., and the rate of fall of level is:

$$r_2 = 12\ (Q_o - Q_i - q_1)\,/\,(\pi R^2) \text{ in. per min.}$$

and the time for the level to fall a distance $2l$ *is*

$$t_2 = 2l/r_2 \text{ minutes.}$$

Fig. 3-4 shows the relation between inflow (Q_i) from main supply, the make-up flow (q_1, q_2) and the level for a specific set of conditions—R is 4 ft., l is 6 in., Q_o is 100 cfm., Q_i is 80 cfm., q_1 is 4 cfm., q_2 is 26 cfm. These values produce a t_1 of 8 min. and a t_2 of 3 min.

Note that the level cannot deviate by more than the preset ± 6 in. unless the main supply drops below 74 cu. ft. per min. (when the vessel would commence to empty) or rises above 96 cu. ft. per min. (when the vessel would commence to fill up).

Case (2)—*Outflow Variable.* Exactly the same considerations apply if the outflow varies as the result of a new level of demand from Plant 2 in Fig. 3-3—provided the condition $Q_i + q_2 < Q_o < Q_i + q_i$ holds for all values of Q_i and Q_o likely to occur.

If changes in supply or demand are very variable, it will be impossible to arrange the proportion of "make up" flow so that the period of operation of the control valve is reasonably slow for all conditions. For small changes of supply or demand flow, the rate of increase or decrease of level will be too rapid. In such circumstances valve wear will also be rapid and any time lags in the system will become appreciable and overshoot will occur as explained below. In these conditions another form of control should be used.

EFFECTS OF LAGS ON 2-STEP CONTROL

It has been assumed that measuring and controller lags are negligible. In practice they will generally be so in level control applications. However, it is interesting to examine the effect of a total measuring and control transmission lag of t minutes, as this will be an important consideration in temperature control.

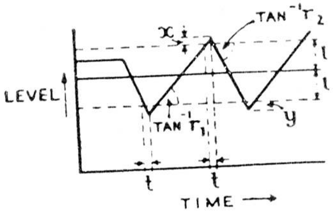


Fig. 3-5. Effect of lag on response of system in Fig. 3-3.

The valve will take up its new setting t minutes after the level has deviated by $\pm\, l$ in. from the mean value, instead of immediately this occurs. Therefore the rate of rise or fall will continue unchanged for another t minutes. The result will be an "overshoot" x on rising level and y on falling level, where $x = r_1 . t$ and $y = r_2 . t$ (Fig. 3-5). Alternately the percentage overshoots are $100\, t/t_1$ and $100\, t/t_2$ respectively. For 10 percent overshoot on falling level, $t = t_2/10$. In case (1) above $t_2 = 3$ min. and $t = t_2/10 = 0.3$ min. The increase in deviation would be 1/10 of 6 in. = 0.6 in.

Note that the slopes of the curve for rising and falling level are r_1 and r_2. These curves show the reaction of the process to the disturbance and are part of the "process reaction curve," which shows the change in controlled condition caused by a disturbance in supply or load.

PERFORMANCE OF 2-STEP LEVEL CONTROLLER

It is clear that the two-step controller can meet the first requirement—namely, to keep the level within the prescribed limits of ± 6 in. It would, however, be a help to the flow controller on the output, which is the feed to Plant 2, if the pressure at the base of the vessel were kept as constant as possible. In particular, cycling of level may cause appreciable disturbance in the flow control system if the periods of oscillation happen to coincide.

If the tank is closed and under a pressure (P) very much greater than the pressure due to the head of liquid in the vessel, level variations of the order of ± 6 in. will be completely negligible. For example, if $P = 250$ lb. per sq. in., 6 in. change in level, equivalent to 0.22 lb. per sq. in., represents less than 0.1 percent change in total pressure. If the tank is open, and the depth of liquid 60 in., then a variation of 6 in. will cause a change of head of 10 percent, which is considerable. Applications will, therefore, arise in which it is necessary to control the level as closely as possible, while retaining the simple two-step controller. The main factor which determines the closeness of level control in a single vessel is the capacity of the vessel. In the same way, it will be seen later that thermal capacity plays the same part in temperature control by a two-step controller.

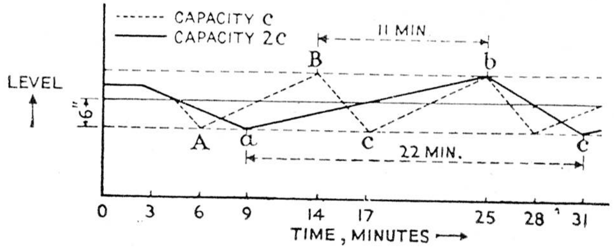


Fig. 3-6. Effect of change of capacity of storage tank.

EFFECT OF CAPACITY

As shown by the equations for r_1 and r_2, the rate of change of level is inversely proportional to R^2; hence the rate is inversely proportional to the capacity of the vessel per unit length (C). If the capacity of the storage vessel is doubled, the period of cycling will increase from 11 min. to 22 min., the rate of change of level will be halved, and the valve will change setting half as often. (Fig. 3-6).

Note also that the frequency of the operation of the valve depends on the difference between the high and low levels.

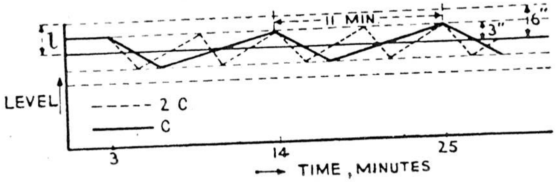


Fig. 3-7. Effect of change of level limits.

As the level difference is decreased, the frequency of operation increases (Fig. 3-7). As there is an upper limit to the frequency of operation of a valve, the level difference cannot be reduced too far.

It follows that if C is made large enough, it will be possible to make the deviations in level very small and yet have slow cycling of the valve between its two positions. Capacity alone is, therefore, always an aid to smooth control.

If, however, resistances are associated with capacities, as in the two-vessel system of Fig. 3-8, transfer lags are introduced and are always a disadvantage, as we have seen in the case of detecting element lag.

Effect of Resistance and Capacity

When resistance is associated with the capacity, the result is an exponential process reaction curve. For example, considering the right-hand tank in Fig. 3-8 alone, with capacity C_2 per unit depth and a resistance R_2 to outflow, a constant rate of inflow would change the level at a rate shown by the dotted curve (a) in Fig. 3-9. The time constant of the system is C_2R_2.

Fig. 3-8. A two-capacity system with associated resistances to flow.

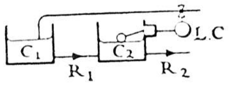
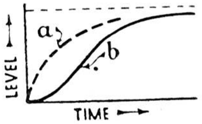


Fig. 3-9. Exponential and "delayed-start" exponential caused by resistances.



Consider next the two tanks in Fig. 3-8 of capacity per unit length C_1 and C_2, connected by a pipe which has a resistance R_1 to flow of liquid. Flow of liquid from the second tank is dependent on resistance R_2. It is at once obvious that if the flow to C_1 is increased, the rise of level in C_2 will be slow at first and follow a "delayed-start" exponential, as in Fig. 3-9, b. The shape of this curve depends on the two time-constants C_1R_1 and C_2R_2. This curve shows how the level in tank C_2 varies after the low limit has been reached and additional flow rate into C_2 has been made to increase the level again.

The effect of transfer lag in a level control system is to cause overshoot and "rounding off" of the straight-line graph of Figs. 3-6, 7, 8 as in Fig. 3-10. Such conditions must be avoided in an actual plant.

The example is mainly of interest as being analogous to the temperature-control problem in which two-capacity systems are common and unavoidable.

Inherent Regulation

An important plant characteristic in all control problems is that of inherent regulation, which is defined as follows (Definition 2304): "A property of a process by which, in the absence of control, equilibrium is reached after a disturbance." Most processes possess this property to some degree. The greater the inherent regulation, the more easy is the automatic control of the process.

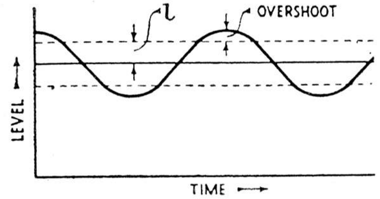


Fig. 3-10. Overshoot and rounding of curves caused by transfer lag.

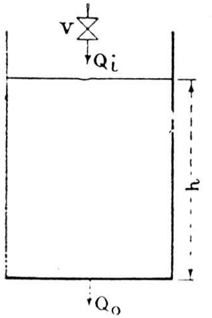


Fig. 3-11. Open tank with inflow and outflow.

Consider the conditions governing the level in a tank (Fig. 3-11) open to atmosphere. In the absence of control, the level stabilizes at a height (h) so that inflow (Q_i) is equal to outflow (Q_o). Then $Q_i = Q_o = k\sqrt{h}$ (k is a constant).

If Q_i is increased to Q_i', the level will rise until $Q_i' = Q_o' = k\sqrt{h'}$. The level will then remain stable at height h'. This system therefore possesses inherent regulation.

If the outflow were controlled by a constant displacement pump, or a flow controller (as in Fig. 3-3), instead of by the head in the tank, any sustained change in Q_i would cause a continuous change in level until the tank overflowed or emptied. There would be no inherent regulation.

Potential Value and Potential Deviation

The concept of the "potential value" of the change brought about by a change of setting of the regulating unit is important in the study of plant problems. Potential value (definition 2206) is: "The equilibrium value of the controlled condition which would be attained for any particular adjustment of the regulating unit in the absence of changes in external conditions . . . which affect the process." For example, the value of h corresponding to the equilibrium level for a setting of valve V (to give Q_i) is the potential value of the setting. Usually a knowledge of the potential *change* of controlled condition due to a change of setting of regulating unit is useful. If 1 percent. change in setting of a pneumatically operated valve V gives 0.5 percent. change in h (60 in.) then the potential change of level for 1 lb. per sq. in. change of pressure on the valve diaphragm (1/12th of full opening) is $60 \times 0.5/12 = 2.5$ in. (This assumes linearity for small changes in h.)

Potential deviation expresses a most useful idea which is helpful in defining the efficiency of a control system in terms of its inherent regulation. The potential deviation is used to define the change in controlled condition, due to a given disturbance, which would occur in the absence of control. For example, the potential deviation due to a change in outflow rate (Q_o) in the system of Fig. 3-11 is a change, say Δh, in h. With two-step control (with no lags) the deviation is actually limited to, say l. Thus we can use $\Delta h/l$ as a measure of the efficiency of the system—that is, potential deviation/max. actual deviation.

The greater the inherent regulation (*i.e.*, the smaller the potential deviation), the easier the control becomes.

Since the object of control is to make the deviation l small, and since the larger Δh is the more difficult is the control, this ratio gives a good measure of the efficiency of the control. The larger the ratio is the more efficient is the control.

This ratio will be very useful when continuous control is discussed.

SUMMARY OF EFFECT OF PLANT CHARACTERISTICS ON TWO-STEP CONTROL

Level control has been used to illustrate simply the effects of plant characteristics on the performance of a two-step controller. Before taking the more difficult case of temperature control, let us summarize these effects.

1. Process reaction rate does not affect the efficiency of two-step control if the plant has no appreciable process lags and if the controller and regulating unit has no appreciable lag.

2. Similarly, demand changes can be large or small (provided they remain within a prescribed range which the change in valve settings can meet) when no lags exist.*

---

*Provided the frequency of valve repositioning is not too great from the mechanical point of view.

3. Increase of demand side capacity increases the stability of the system.

4. Inherent regulation makes control easier.

5. Lags in either plant or controller tend to cause "overshoot" and temporary changes of mean level, so that when plant lags are considerable, successful two-step control can only be obtained if:

(*a*) Process reaction is slow (*i.e.*, demand side capacity is large).
(*b*) Demand changes are small.
(*c*) Measuring and controller lags are small.

CHAPTER IV

TWO-STEP CONTROL OF TEMPERATURE

The basic principles which have been illustrated in considering two-step level control now can be applied to temperature control.

THE PROCESS REACTION CURVE

A valuable quantitative idea of the ease or difficulty of controlling any process can be obtained by drawing curves, known as process reaction curves, to show the variation of controlled condition (in the absence of control) due to (a) supply changes and (b) load changes.

In discussing level control, it has been seen that the following information can be obtained from these curves:

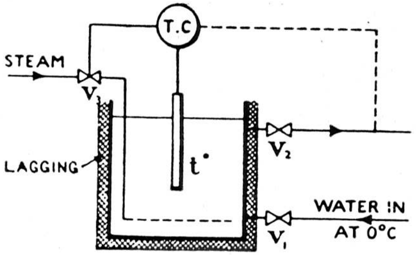


Fig. 4-1. Temperature-control system in which water is heated by steam injection.

(1) The mean rate of change of controlled condition (r).

(2) The initial value of r, which determines the response of the controller at the commencement of the disturbance.

(3) The inherent regulation of the process.

Example (i). Consider the vessel in Fig. 4-1, in which water is heated by steam injection. Let valves V_1 and V_2 be closed so that, if the vessel is well lagged, there are no appreciable heat losses. Then if steam is injected the rate of rise in temperature will be constant and proportional to the steam rate, as shown by curves a and b in Fig. 4-2.

Example (*ii*). Next let valves V_1 and V_2 be opened, so that water flows into the vessel at a rate (Q), is heated through t degrees, and flows out carrying away heat at a rate equal to Qt. If we could hold the amount of heat (Qt) constant, the change in temperature of the water in the vessel would still be linear with time as in Fig. 4-2, curve a, and a change in steam rate would merely alter the rate of temperature change, curve b.

Note. (a) If the specific heat of the condensed water is insignificant in comparison with the latent heat of the steam, the transfer of heat from steam to the water in the vessel does not depend on the temperature of the water—that is, heat is added irrespective of the water temperature at a constant rate, just as water added to a tank at constant rate gives a constant rate of rise of level.

(b) There is no transfer lag in the process because there is no thermal resistance, or loss of heat depending on a temperature difference.

The time which elapses while the temperature of the water is being raised by the required amount is due to the finite rate of supply of heat (as steam) and to the thermal capacity of the water.

Example (*iii*). Next take the more practical condition in which the heat (Qt) taken from the system is not held constant. We now have conditions analogous to Fig. 3-11 for level control, and so we shall expect inherent regulation. The function of the two-step controller is to hold the water in the vessel at t degrees so that the incoming water leaves at t degrees. After equilibrium has been established, let a supply disturbance occur in the form of an increased steam pressure upstream of V_3, and consequent increased steam supply. The extra heat-supply rate will increase the water temperature, but not linearly because the loss of heat is no longer constant but proportional to the temperature of the water. The process reaction curve for a supply change is therefore as shown by the dotted curve in Fig. 4-2.

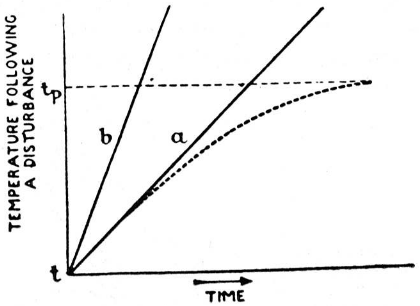


Fig. 4-2. Temperature of water in Fig. 4-1 for various conditions.

Note. (a). In the absence of control, the final temperature attained would be the "potential temperature" (t_p) such that the extra heat supplied equalled the extra heat lost, (Q) ($t_p - t$). The "potential deviation" due to the supply change is ($t_p - t$).

(*b*) The system possesses inherent regulation, which will assist the controller; if $(t_p - t)$ is small, inherent regulation is large.

(*c*) The reaction rate is initially the same as in (*a*), and hence no disadvantage to the controller is introduced at the beginning of the change.

(*d*) The shape of the dotted curve in Fig. 4-2 is typical of that produced by a transfer lag.

If C is large, changes due to supply disturbances will be slow, and if Q is large the inherent regulation will be high for supply disturbances. Hence control will be stable for suppy variations.

Example (*iv*). Assume now that Q increases by $\triangle Q$, giving a load change. The extra rate of heat supply required is $(\triangle Q)(t)$. The temperature t will commence to fall exponentially towards the potential value of temperature corresponding to the disturbance. Here again a large value of C will prevent rapid changes; the greater the inherent regulation, the less the potential change will be in the absence of control.

These considerations indicate that a system of the type of Fig. 4-1 with a large demand-side capacity, and considerable inherent regulation, presents an easy temperature-control problem. The shape of the process reaction curve at the commencement of a change is favorable.

Two-step control therefore can be applied safely in such a system.

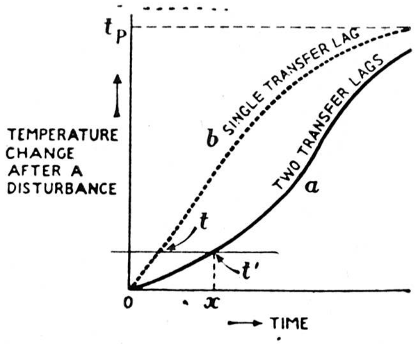


Fig. 4-3. Effect on process reaction curve of transfer lags introduced by both supply-side capacity-resistance and demand-side capacity-resistance.

SYSTEMS WITH SEVERAL CAPACITIES AND RESISTANCES

In many applications, however, there are several capacities and resistances and, consequently, several sources of transfer lag. The two most common sources are (a) supply capacity with heat transfer resistance between supply and demand, and (b) detecting-element transfer lag.

The steps for eliminating the latter have been discussed and should be taken in all temperature-control systems; they are especially unfavorable for two-step control. The former are inherent in the plant design and are also unfavorable to two-step control.

The two-capacity-resistance level-problem discussed previously can usually be avoided, but the analogous temperature problem cannot be avoided. In general it is better to apply a continuous method of control to systems with several capacities and resistances.

Fig. 4-3 shows the effect on the process reaction curve of transfer lag introduced by a supply-side capacity and resistance, in addition to transfer lag due to demand side. The initial slow change (*ox*) is the main trouble because while the disturbance is "coming through" to the demand side, the supply disturbance (masked by the slow initial change) remains only slightly corrected. In two-step control the departure from desired value would be detected at a time given by the curve (*a*) at time *t'*, considerably later than *t* if curve (*b*) had applied. Hence overshoot will occur. The control obtained after a demand change is shown in Fig. 4-4 for a system with two transfer lags.

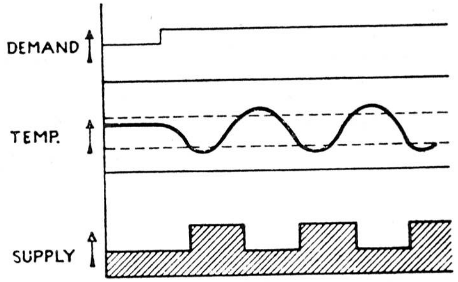


Fig. 4-4. Control obtained after a demand change in a system with two transfer-lags.

Note. (1) Any measuring lag will increase the difficulty of control and result in greater overshoot.

Distance-velocity lag, such as would be given in the system of Fig. 4-1 if the detecting element were placed some distance along the outflow pipe (as shown dotted), can be avoided usually by correct positioning of the detecting element.

(ii) It is important to remember that measuring transfer lag causes the measuring unit to read *low* during any cyclic disturbance of the controlled condition. It is therefore possible for the controlled temperature to deviate seriously outside the high and low limits due to this cause alone. If the measuring unit operates a recorder the same error will be made in the record which is therefore useless for showing whether or not the controller is keeping the temperature within the required limits. Not only should transfer lag in the measuring unit be reduced to the minimum, but the rate of cycling also must be reduced as far as possible. The lower the rate of change of controlled condition, the less will be the error due to transfer lag in the measurement.

CONDITIONS FOR SUCCESSFUL TWO-STEP CONTROL

The magnitudes of capacities, lags, and changes in supply and demand in the plant determine the success of the installation. Large capacity on the demand side and small capacity on the supply side, together with low value of lags, (especially transfer lags) make for good control. Two-step control can be used in these conditions.

Measuring and controller lags are as important as process lags and the best condition is when one lag is much larger than the rest. The worst condition arises when the total transfer lag is made up of a number of approximately equal lags. If two or more considerable transfer lags exist, two-step control should not in general be used.

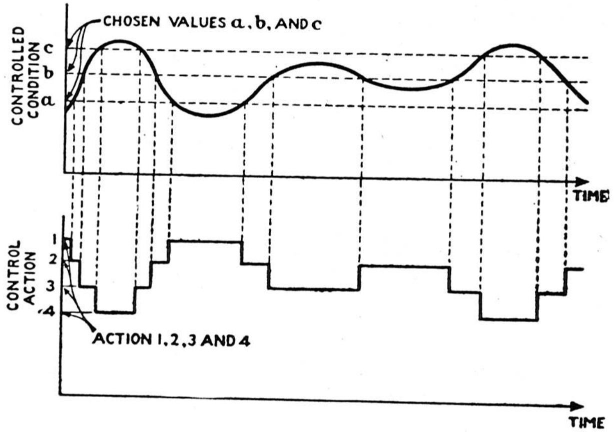


Fig. 4-5. Multi-step control, in which control action takes place at chosen values (a, b, and c) of the controlled condition.

Large changes in supply or demand make it impossible to set the regulating unit with high and low values suitable for covering the whole range of possible changes.

MULTI-STEP ACTION

To meet the need for more flexibility to deal with wide fluctutations of supply and demand, multi-step action is sometimes used. It is defined as (Definition 2410): A control action in which predetermined control actions take place in two or more chosen values of the controlled condition. Fig. 4-5, reproduced from the B.S.I. Glossary of Control Terms, illustrates the action.

EXAMPLES OF PLANT USE OF TWO-STEP CONTROL

(1) *Level*—Stock tanks and feed tanks; surge vessels; bottom product level in continuous stills (usually proportional action is used).

(2) *Temperature*—Small furnaces with electric or gas heating and large continuous furnaces where the load is nearly constant; preheaters and oil and salt baths; batch processes in which the chemical action is not strongly exothermic or endothermic and when the temperature is not critical. Many batch processes fall into this category. Tanks and baths, such as are used for plating, etc., where changes in demand are small.

(3) *Pressure*—Where pressure is not a matter of flow control, *e.g.*, air compressor and receiver.

CHAPTER V

PROPORTIONAL CONTROL

Discontinuous methods of control are in general cheaper to apply than continuous methods. The latter are, however, widely used where the former are not capable of giving sufficiently close control.

Practically all continuous controllers are based on proportional action. Wherever possible, proportional action is used alone, but process characteristics often demand the addition of either integral or derivative action, or both. As its name implies, proportional action is (B.S.I. definition 2404): A control action varying directly with deviation—that is,

$$V = -K_1\theta$$

where V is control action on regulating unit, θ is deviation of controlled condition from the desired value, and K_1 is a coefficient.

The negative sign in the equation shows that the action is directed to counteract the deviation.

If the control action V on the regulating unit causes the regulator to produce a potential correction* Θ of the controlled condition, such that $\Theta = (K_v)\ (V)$ then we can write:—

$$\Theta = -K_1(K_v)(\theta) \qquad (1)$$

where $\mu = K_vK_1$ and is known as *the proportional control factor.*

The definition of proportional control factor is as follows (B.S.I. definition 2505): The ratio of the potential correction to the deviation in proportional control.

OFFSET AND PROPORTIONAL BAND

As the position of the regulating unit is proportional to the deviation (θ), it follows that for each value of θ there is a specific regulating unit position and, therefore, a given input to the system. If the demand increases, the regulating unit can only increase input to satisfy this demand by moving to a new position. But this movement can only be caused by an increase in deviation (θ). Therefore the process temperature (or other controlled condition) must decrease until such a deviation exists as will cause the regulator to open sufficiently to give the increased input to bring the process to equilibrium. If no further process changes occur, this equilibrium will be maintained but at a lower level than the desired value. The new level at which the temperature is controlled is defined as the "control point," and the difference between desired value and control point is called *offset* (Fig. 5-1).

The magnitude of the offset for a given load change is dependent on the value of K_1, which determines the regulating unit movement per unit deviation. If K_1 is large, offset will be small and *vice versa.* The value of K_1 is determined by the "proportional band" of the controller, which is (B.S.I. definition 2502): The range of values of the controlled condition which operates the regulating unit over its full range. This range is expressed as a percentage of the scale range. (Fig. 5-2).

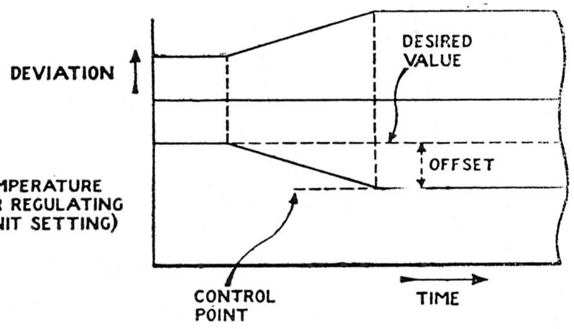


Fig. 5-1. Offset produced by change in load.

It is evident that to keep offset small, the proportional band must be narrow; also, that the control point must remain within the proportional band because when the deviation reaches the limits of the band, the regulating unit has also reached the limits of its travel. If any further demand is made by the process, the regulating unit will be "over ranged" and the temperature will continue to drift unless it is corrected at a new equilibrium level by the inherent regulation of the process.

STABILITY

The need for stability sets a limit to the narrowness of the proportional band which can be used. If the band is made too narrow, any disturbance will cause the system to go into oscillation with an amplitude that may increase to a large value. Similarly, a sustained change in supply or demand will be followed by sustained "hunting."

In setting up a proportional controller a compromise must be made between narrowing the proportional band

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* "Potential correction" is the change of potential value of the controlled condition due to the movement of the regulating unit.

to decrease offset and keeping it wide enough to prevent instability.

Unless a narrow band can be used, proportional control action is inadequate for any process in which large load changes are likely to occur and in which the resulting offset cannot be tolerated.

Since the proportional controller is the simplest continuous controller (and therefore the cheapest in initial cost, adjustment at starting up the plant, and subsequent maintenance) we shall examine the process characteristics which permit a narrow band to be used without instability.

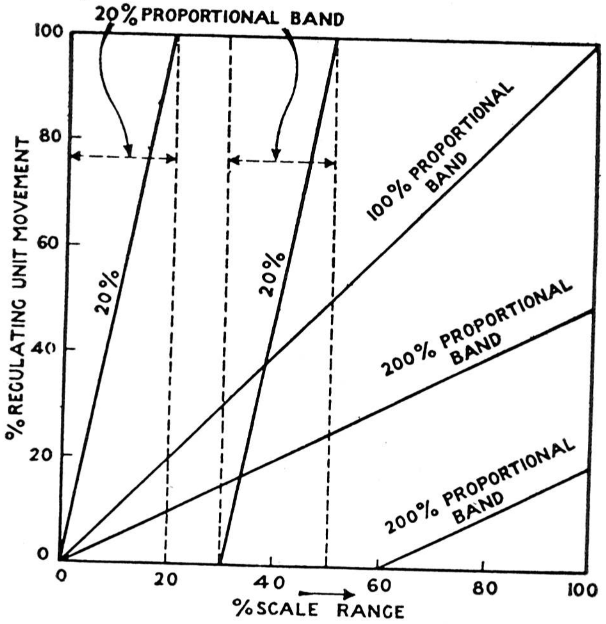

Fig. 5-2. Widths of various proportional bands of a controller.

Distinction Between "Action" and "Control"

Confusion can easily arise between the meaning of "action" and "control" and between the coefficients defining the action and the control factors. In addition to K_1 and μ, the symbols K_0 and γ, and K_2 and ρ will appear later as the corresponding coefficients and factors for integral and derivative controllers respectively.

Control characteristics usually are defined by use of μ, S, and R, where S is μ/γ, and R is ρ/μ. The terms ρ, γ and K_1, K_2 and K_0 generally enter only into the *explanation* of control theory and controller operation.

The controller *action* defines the response of the controller itself; *control* refers to the whole control system, and depends on the regulating unit and plant characteristics.

Hence, if the pneumatic controller has proportional action, the pressure output from the controller will be proportional to the deviation. If the control system is said to be operating under proportional control, then the potential correction applied by the regulating unit is proportional to the deviation, *i.e.*, the potential change in controlled condition is proportional to the deviation.

The distinction is necessary because the regulating unit has not necessarily a linear characteristic. If it has not, although controller action is proportional, the regulating unit may give a correction perhaps proportional to the square of the change in pressure applied to it. Clearly, the potential correction will no longer be proportional to the deviation, but to its square.

For present purposes it is sufficient to assume linearity in the system, including the regulating unit and plant.

Criteria of Good Control

The first essential in studying the relationship between plant and controller characteristics is to establish the criteria for good control.

A control system is required to achieve the following conditions:

(i) Small deviation from desired value following a disturbance, *i.e.*, to give a high "deviation reduction factor."

(ii) Quick return to control point* after a disturbance causing oscillation, *i.e.*, to give a satisfactory value (*e.g.*, *e*:1) of the "subsidence ratio" at short oscillating period.

(iii) Small deviation of controlled condition from the desired value when conditions are steady, in spite of changes which may have occurred in supply or demand in the plant, *i.e.*, to keep "offset" at a minimum.

The relative importance of (i), (ii), and (iii) varies from process to process. Plant requirements in any given application will decide which of these three conditions is the most important.

Recovery after a Disturbance

The curves in Fig. 5-3 show three representative types of record given by a proportional control system following a sudden change in demand. They differ from the type of record in Fig. 5-1 in exhibiting "overshoot" and subsequent

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***B.S.I. Definition No. 2201, "Control point: the value of the controlled condition which the automatic controller actually maintains under steady-state conditions."**

oscillation, which is damped out at a rate depending on the width of the proportional band.

The difference is due to the time lags in the system. Without time lags "overshoot" would not occur because immediate corrective action would be taken by the controller. Oscillations could neither be set up nor maintained. In Fig. 5-1 the plant conditions are changing so slowly that the time lags are negligible and the control can therefore succeed in making corrections to the setting of the regulating unit sufficiently rapidly to follow the changing demand at each instant.

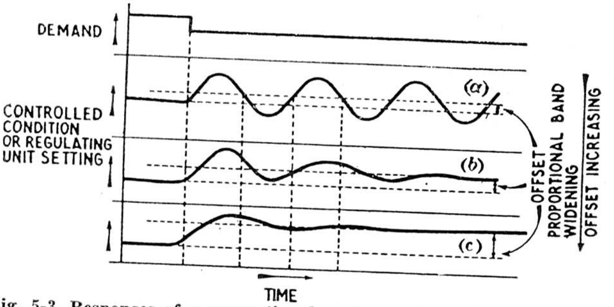


Fig. 5-3. Responses of a proportional-control system following a sudden change in demand for various proportional bands.

It can be seen from Fig. 5-3 that, as the proportional band is widened, the oscillations set up in the control loop are damped out more quickly. At the same time offset increases. Also, widening the proportional band increases the period of the oscillations.

Deviation Reduction Factor

In any stable system the amplitude of oscillation of the value of the controlled condition is as shown by curves (*a*), (*b*) or (*c*) in Fig. 5-3. The amplitude is never greater than at the first peak following a disturbance; *i.e.*, the initial overshoot is the greatest (say θ_m). The value of θ_m will depend on the plant characteristics as well as on those of the controller. Therefore in order to provide a measure of the performance of the controller, the maximum deviation (θ_m) with control can be compared to the deviation that would have occurred in the absence of control (say θ_p). It will be remembered that the value of θ_p depends on the inherent regulation of the plant and that θ_p is known as the potential deviation.

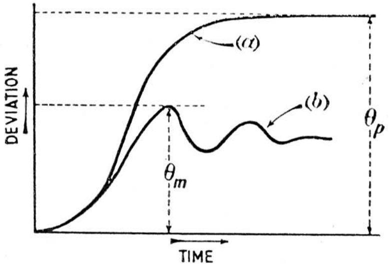
In Fig. 5-4 the deviation of the controlled condition, for a given process following a distrubance in demand, is plotted against time for (*a*) no control, and (*b*) proportional control. The deviation which would have occurred in the absence of control (θ_p) is reduced to a maximum deviation of θ_m by the controller. The ratio θ_p/θ_m therefore gives a good measure of the efficiency of control in keeping overshoot to a minimum. In the absence of a standard term for this ratio, it may be called the "deviation reduction factor."

It can be shown that the deviation reduction factor is in general proportional to the value of the proportion control factor (μ) and hence, to minimize overshoot, a high value of μ is desirable.

Subsidence Ratio

Of the three types of recovery shown in Fig. 5-3, that of curve (*b*) offers the best compromise between quick damping out of the oscillations and magnitude of offset. It is a matter of common experience that damping increases as the proportional band is widened (so that steady running at the control point is attained more quickly) but that the offset is increased. It will also be noticed that the period of the oscillation increases as the proportional band widens.

Fig. 5-4. Deviation of controlled condition following a disturbance in demand for (a) no control, and (b) proportional control.



It is convenient to have a measure of the rate of damping of the oscillations and (again in absence of a standard term) it can be called the "subsidence ratio," defined as: "the ratio of the peak of one oscillation to that of the succeeding peak in the same direction," *i.e.* x/y in Fig. 5-5.

The best value of the subsidence ratio must be selected for each process. It may vary from 2 to 4 or more, according to the application. For the purpose of this discussion a value of e: 1 is taken as a working average value, which will be quite suitable for many installations, where e is 2.7183, the base of natural logarithms.

It should be noted that the subsidence ratio only determines the *number* of oscillations which will occur before steady conditions are achieved. Therefore, in order to achieve rapid return to steady running, the period of the oscillations must be small.

We must therefore examine the conditions which determine the period of the oscillations set up in a control system by a disturbance in the process. The simplest approach

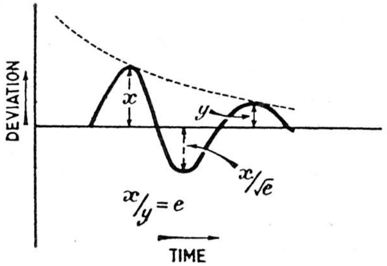


Fig. 5-5. Subsidence ratio of a damped wave form.

is to assume in the first place that a step disturbance occurs in the supply, *i.e.*, that a sudden, sustained disturbance enters the control loop through the regulating unit. Further, let us assume that the disturbance sets up "hunting" in the control system and therefore that the recorder operating from the detecting element commences to produce that most familiar of all records, shown in Fig. 5-3, curve (*a*), which has a sine wave form. Just as we can adjust the controller on the plant to give stable control by first obtaining this type of record and then readjusting to obtain the damped wave form (Fig. 5-5) on the recorder, so we can investigate theoretically the conditions which give the sine wave oscillation of constant amplitude and then find the adjustments necessary in these conditions to give damped oscillations with subsidence ratio e:1.

CHAPTER VI

MATCHING PROPORTIONAL CONTROLLER TO PLANT

It has now been shown that good control requires (i) a high deviation-reduction factor, (ii) a short operating period, and (iii) minimum offset.

We have seen that each of these factors is dependent on the proportional control factor (μ) and that to obtain best control it is necessary to use the highest value of μ which is compatible with control-system stability.

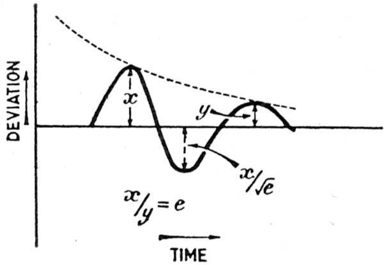
In the following analysis it will be shown how the value of μ which can be used depends on the plant characteristics, and what measures can be taken when the value of μ is limited to a magnitude insufficient to give satisfactory control in the plant conditions anticipated.

First it is necessary to examine the effects of attenuation and phase lag suffered by a disturbance as it passes through a plant which is not under automatic control.

ATTENUATION AND PHASE CHANGE IN PLANT

Every plant has time lags which decrease the amplitude of a continuously varying disturbance passing through it, and which also produce a phase lag in that disturbance. Similar conditions apply to each part of the closed-loop control system. Capacities and resistances give rise to transfer lags. It has also been seen that pure distance-velocity lag produces a delay in transmission of a change from one part of a plant to another, but does not decrease the magnitude of the disturbance. Transfer lags, on the other hand, produce both delay and decrease in magnitude of a disturbance passing through the plant.

It is not easy to calculate the lags even in a comparatively simple system such as a temperature-detecting element in a protective pocket. It is much more difficult to calculate the time lags in plant components such as heat exchangers, stills, evaporators and so on, even when the plant is new. In operating conditions, when the effects of dirt films on the surfaces and other unpredictable factors are important, the calculation is virtually impossible. The lag must therefore be determined experimentally, and one method is described.



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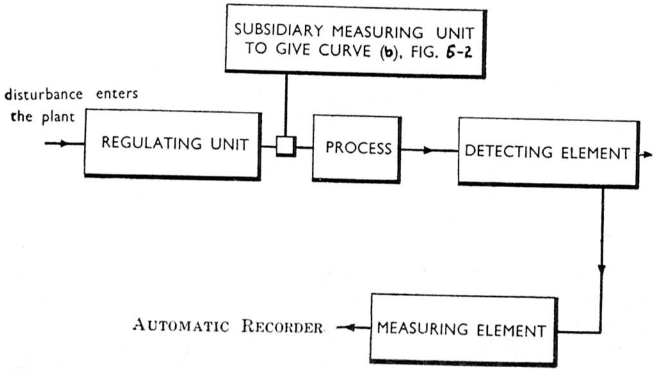

Fig. 6-1. Instruments for measuring disturbance at input and output of plant. Subsidiary measuring unit gives curve (b) of Fig. 6-2; measuring element gives curve (a) of Fig. 6-2.

The effect of time lags in a plant could be examined by recording the magnitude of a disturbance at two points simultaneously. For example, in Fig. 6-1 a plant is shown provided with a subsidiary detecting element near the regulating unit and a second element some distance downstream of the regulating unit. If a disturbance is imposed on the plant by varying the psi. to the regulating unit, the two records obtained might give the curves of Fig. 6-2. For ease of interpretation a continuous disturbance varying sinoidally with time has been taken. The plant, it should be noted, is not controlled automatically or manually while the records of the disturbance are being taken.

Comparison of the two records in Fig. 6-2 shows that in its passage through the plant the disturbance is decreased in amplitude in the ratio α_1/α_2. This ratio is the "attenuation" (A) suffered by the disturbance due to its passage through the capacities and resistances of the plant.

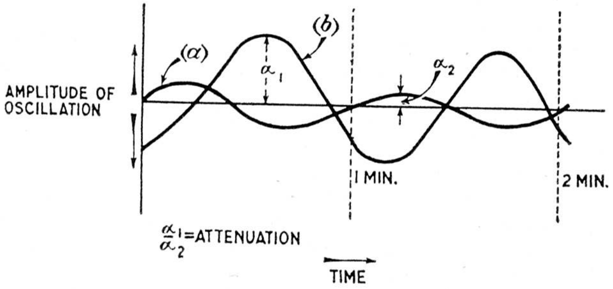

Fig. 6-2. Curves illustrating attenuation and phase lag in plant. Curve (b) is sinoidal disturbance imposed on regulator at input to plant; curve (a) is record of detecting element at "end" of plant.

It is also evident that the outcoming disturbance is about 180 degrees out of phase with the incoming disturbance; that is, it has suffered a phase lag of approximately 180 degrees.

If the period of the disturbance is reduced, the attenuation and the phase lag are both increased, but not in general in the same ratio.

If the experiment is repeated for disturbances of various periods, plots can be made to show the way in which attenuation and phase lag depend on the period of the disturbance. Examples are shown in Figs. 6-3 and 6-4, which can be more conveniently plotted on a single diagram, known as the "frequency response" diagram, such as Fig. 6-5. Note that the phase lag is plotted on a linear scale whereas the period and attenuation are plotted on a log scale.

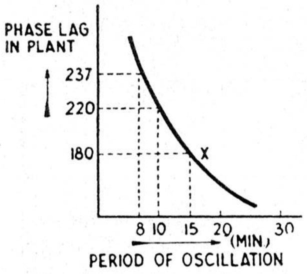

Fig. 6-3. Curve of phase lag in plant vs. period of oscillation.

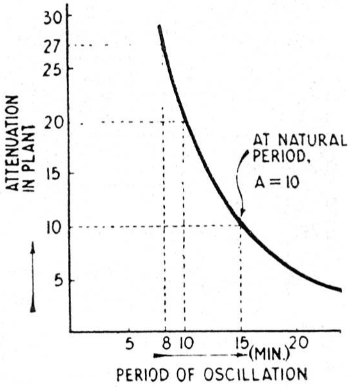

Fig. 6-4. Curve of attenuation in plant vs. period of oscillation.

The information given about the plant characteristics in Fig. 6-5 is essential for logical design of a system to control the plant. A method of obtaining the information for plotting the frequency-response diagram is therefore described.

An Analyzer For Obtaining Plant Characteristics

Assume that the plant is controlled by a pneumatically operated valve. All we have to do is to apply a sinoidal variation of air pressure to the valve, record this varying pressure, and record (on the same chart) the resulting variation of signal from a detecting element installed at a suitable location in the plant. The plant is not controlled during this experiment.

A piece of equipment for doing this has been described in the literature.* It has provision for varying the period, amplitude, and mean value of the sinoidal air pressure applied to the regulating unit. It utilizes a linear roll chart for convenience in comparing the two curves, which correspond to curves (a) and (b) in Fig. 6-2. The design of this analyzer (Fig. 6-6) is shown in Fig. 6-7. Fig. 6-8 shows the arrangement of equipment and plant for carrying out an analysis. It is convenient to feed the signal from whatever element is used to a pneumatic proportional controller and to apply the air pressure from this controller to the analyzer.

The attenuation and phase lag produced by the plant at the periods used in the analysis are easily determined from the two records on the analyzer chart, and a frequency-response diagram, such as in Fig. 6-5, can be made from the records.

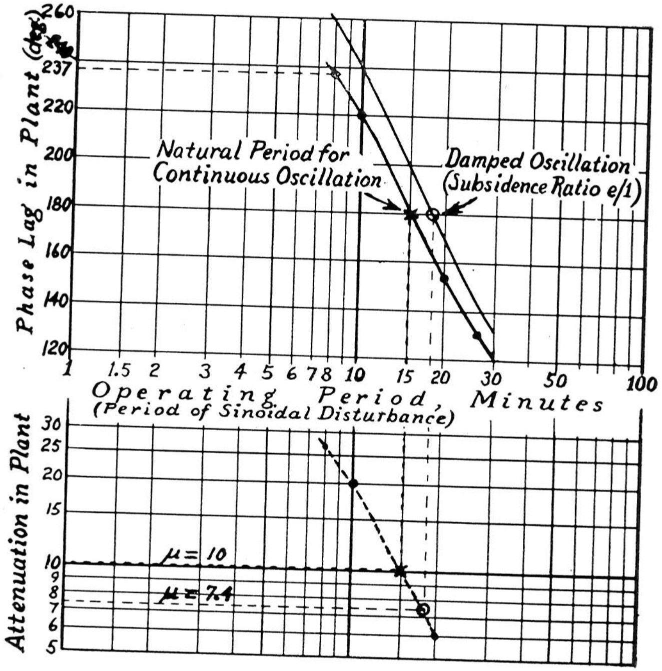

Fig. 6-5. Frequency-response diagram.

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* A. R. Aikman, "A Portable Instrument for Control Analysis," *Instrument Practice*, Vol. 5, page 393, 1951.

J. Halsall, "A Portable Instrument for Control Analysis—the Electrical Equipment," *Instrument Practice*, Vol. 5, page 793, 1951.

Before use can be made of the data obtained on plant characteristics, it is necessary to know how these determine the controller characteristics required to give optimum quality of control.

It has already been seen that the proportional control factor (μ) must be made as large as possible without introducing instability. Let us now examine the conditions which determine this value of μ in a proportional-action controller.

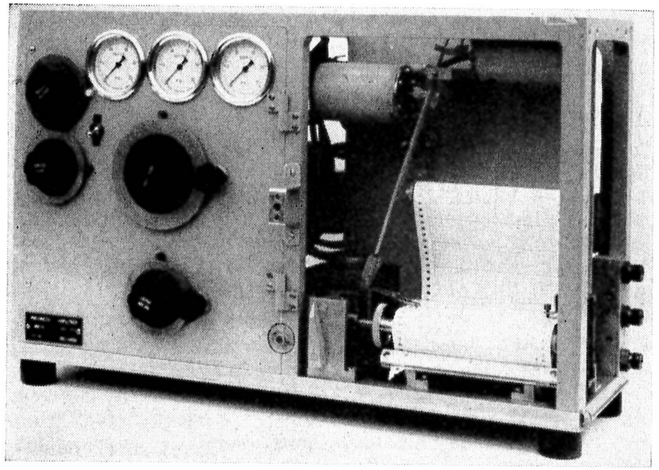

Fig. 6-6. Analyzer for obtaining plant characteristics.

Suppose a step disturbance occurs in the supply to a plant under proportional control. A narrow proportional band will tend to cause oscillations to be set up; as the proportional band is narrowed, the oscillations become less and less damped, as shown in Fig. 5-3 of the preceding chapter.

Let us follow in theory the same procedure as is normally followed in practice in setting up a new proportional controller on the plant—that is, we shall find the value of μ which will cause the plant to "hunt" after a sudden disturbance, and then find how much μ must be reduced in order to give a damped oscillatory curve.

It may reasonably be asked why we should take the trouble to do this when it is a short process to carry out by trial and error on the plant. The reason is that it is only by a knowledge of the fundamental principles of control that results can be predicted, and that a logical approach can be made to difficult problems. Perhaps it is even more important that an engineer responsible for plant design may be persuaded that it is worth while pursuing the matter a little further, with the object of *designing* the plant for good control. As more analyses are made of operating plants, more quantitative information will become available for the use of plant design engineers who are ready to apply it to new plant design.

In order to study the behavior of the system, assume that a sudden disturbance in the form of a step increase in supply is applied to the plant while it is under automatic control. Also assume that, following this disturbance, the control system goes into continuous oscillation and "hunts" steadily. *This could not occur in the absence of the controller.* If oscillations are set up in controlled condition, they must be caused and maintained by the controller.

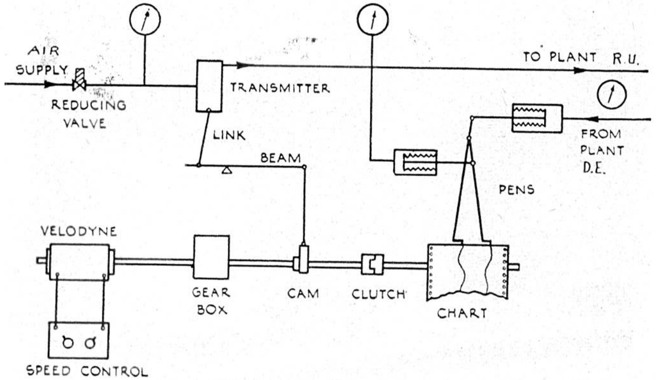

Fig. 6-7. Diagram of analyzer.

If a detecting element is used both at the input and at the output of the process (as in Fig. 6-1), two curves will be produced, as in Fig. 6-2. However, it will now be found that the two curves are exactly 180 degrees out of phase, whereas the curves from the uncontrolled plant of Fig. 6-2 are not necessarily 180 degrees out of phase. The curves in Fig. 6-2 represent the effect of applying a continuous sinoidal disturbance to the plant (via the regulating unit) from an outside source while the plant is uncontrolled; the period of the disturbance can be varied as we please, with consequent variation of the attenuation and phase lag in the plant. However, when oscillation is produced by action of the controller on the regulating unit, the phase lag between the two signals in Fig. 6-2 *must* be 180 degrees. Let us examine how the oscillation is maintained.

Assume that the phase lag in Fig. 6-2 is 180 degrees and that the attenuation is A. If this is true, the disturbance at the output of the plant is 180 degrees out of phase with the disturbance at the input, and is smaller in amplitude by a factor A. If the output is fed to a controller (as in Fig. 6-8) with a gain of A, the output of the controller will be a signal that exactly equals the disturbance at the input of the plant. In addition, a controller always imposes a 180-degree change in phase in the signal. As the signal into the controller is already 180 degrees out of phase with the original disturbance at plant input, the controller adds another 180 degrees, thus producing a 360-degree phase shift. Hence the controller output will be a signal that exactly equals the original disturbance in both amplitude and phase. These are the conditions for sustained oscillation. If the controller in Fig. 6-8 is connected to the regulator under these conditions, the plant will oscillate, or hunt.

It is clear that this cycle of events can only result in a steady, continuous oscillation if the controller gain is equal to A and if the disturbance takes one half the operating period to pass through the plant. Hence the controller gain must equal A. If it is greater, the amplitude of oscillation will build up. If it is less the amplitude will decrease and the oscillation will die out.

There is only one period of operation at which the phase lag in the plant is exactly 180 degrees, and therefore there is only one operating period at which the control system can "hunt" under proportional control. This period is called the *natural period* of the plant under control.

CONTROLLER SETTINGS

Proportional Control

Let us now set up a proportional controller to control the plant whose characteristics are given by Figs. 6-3 and 6-4. The natural period of the plant, at which the phase lag suffered by any disturbance passing through the plant is 180 degrees, is given by point X on the curve in Fig. 6-3 as 15 minutes. Fig. 6-4 shows that at this period the corresponding attenuation (A) is 10. The maximum controller gain must therefore be 10 and by definition, for a proportional controller, controller gain $=$ proportional control factor (μ). Therefore $\mu = 10$.

Determination of Proportional Band Width

Let us consider a temperature control system with air-operated controller and valve. The full working range of both is 12 psi. and the scale range of the measuring unit is 200 deg. C. It is required to set the proportional band so that the proportional control factor (μ) $= 10$.

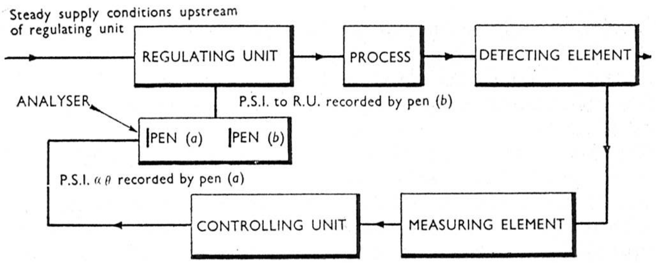

Fig. 6-8. Arrangement of plant and analyzer for obtaining plant characteristics. Pen (b) records sine-wave psi. from analyzer to regulator (or disturbance imposed on input to process); pen (a) records psi. from output of process, or disturbance after passage through plant. The controlling unit shown is used only as transmitter for recording disturbance at output of plant on analyzer chart; it is not controlling regulator.

The corrective action applied to the plant following a deviation of controlled condition from desired value is

$$\Theta = -\mu\,\theta$$

The proportional control factor $\mu = K_1\,K_v$
where * $K_1 = V\,/\,\theta$, and $K_v = \Theta\,/\,V$

(K_1 is the proportional action factor, V is the change in controller output pressure in psi. corresponding to a change θ in deviation.)

To find K_v apply 1 psi. to the valve and note the change in temperature when conditions are again steady, say 5 C. deg. This is the potential correction (Θ / psi.) applied to the valve.

Then $K_v = 5$ C. deg. / psi.
Therefore $\mu = -\,K_1 \times 5$
Hence $K_1 = 10/5 = 2$ psi. / C. deg.

The proportional band must therefore be set so that the controller gives 2 psi. change in output to the valve for a deviation of 1 deg. C.

By definition, the proportional band is the percentage of the scale over which the pen must move to produce the full range of pressure to move the valve from open to shut

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* It should be noted that for proportional control it is necessary to use a valve with a linear relation between Θ and V, as well as proportional action in the controller.

CHAPTER VII

INTEGRAL AND DERIVATIVE CONTROL ACTIONS

Integral action is added to a proportional controller to eliminate offset. Integral control action is defined (B.S.I. definition 2413) as: "A type of control in which potential correction Θ changes at a rate proportional to the deviation." This can be stated in equation form as:

$$d\Theta/dt = -\,\gamma\,\theta = -\,\mu\,(1/S)\,(\theta) \qquad (1)$$

where γ is the integral-control factor[1], μ is the proportional-control factor, and S is the integral-action time.

The integral-control factor (which corresponds to the proportional-factor μ) is not used in practice; the setting dial for integral action on a controller is calibrated in action time, (S) (or in reciprocals of S), which is defined in terms of the proportional action. S is the time taken by the integral action to repeat the proportional action after a step change in deviation.

Fig. 7-1 shows the relation between potential correction (Θ, or regulating unit setting) and time, following a sudden disturbance, for proportional and integral control. The proportional action at once gives a potential correction (P) proportional to the deviation (θ). The integral-action correction (I) commences to increase at a rate proportional to θ and continues to increase as long as the deviation persists. It must, therefore, prevent offset.

After time S, if the deviation is held constant, $I = P$, and the total potential correction (or regulating unit movement) $= 2P$.

Fig. 7-1 has been drawn for simplicity with the offset constant at θ, in spite of the continuously increasing corrective action due to the integral action. This represents the rather unlikely case of a constantly increasing demand which the integral action corrects for in such a way as to maintain the deviation constant at θ.

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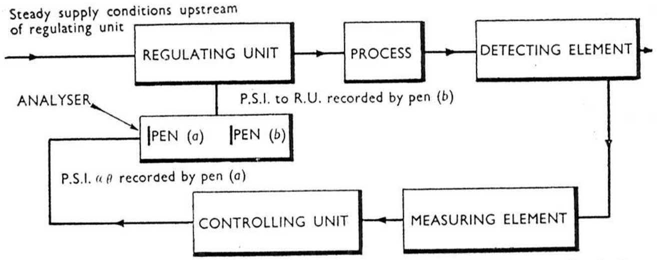
[1] As for μ in proportional control, γ is the product of two factors (K_o, K_v) appropriate to the controller and regulating unit respectively.



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The integral-control factor (which corresponds to the proportional-factor μ) is not used in practice; the setting dial for integral action on a controller is calibrated in action time, (S) (or in reciprocals of S), which is defined in terms of the proportional action. S is the time taken by the integral action to repeat the proportional action after a step change in deviation.

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---

[1] As for μ in proportional control, γ is the product of two factors (K_o, K_v) appropriate to the controller and regulating unit respectively.

At time t after the sudden disturbance the contribution of the integral action is found by integrating equation (1), to give:

$$\Theta = -\mu\,(1/S)\int_0^t \theta\,dt \qquad (2)$$

Therefore, Θ at any time t is proportional to the area between the recorded and desired value on the chart (shaded in Fig. 7-1).

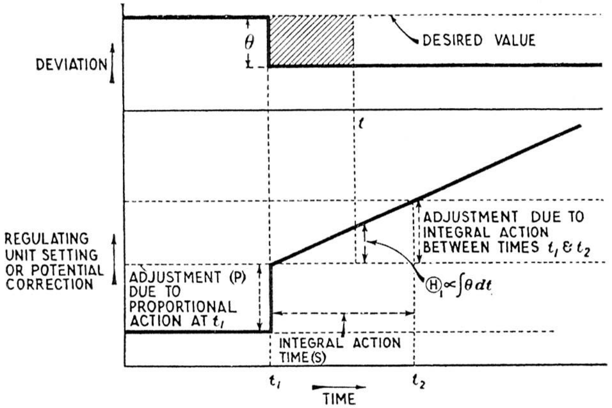

Fig. 7-1. Integral action following a sudden and sustained change in θ, such as might be produced by a load change.

Equation (2) gives rise to the term 'integral" action. It is also known widely as "reset" action, which term arises from the use of integral action to correct offset automatically instead of by "resetting" the desired value by hand.

USE OF INTEGRAL ACTION

The usual object of adding integral action to a proportional controller is to eliminate offset. When large changes occur in plant supply or demand, there often is no alternative to the use of integral action to avoid offset. However, integral action often is used when it is not only unnecessary but also disadvantageous. Quality of control can be measured in terms of the minimum deviation-reduction factor and the time for return to desired value after a disturbance. Both of these criteria depend on the value of μ (the proportional control factor) which can be used. As μ increases, the quality of control improves, as judged by these criteria. The use of integral action decreases the permissible value of μ and therefore causes deterioration of control quality with regard to recovery after a disturbance.

The reason for this is that integral action introduces an additional phase lag into the controller. Fig. 7-2 gives the magnitude of this phase lag in terms of the ratio of operating period (T) to integral-action time (S). The curve can be verified by experiment or derived theoretically[2]. Notice that the phase lag introduced not only depends on the value of S but also increases as the plant period increases.

It is not possible to give precise guidance on the value of integral-action time (S) which should be used in various conditions, but it has been found in practice that a value of S equal to the operating period (T) is about optimum in the general case.

Effect on Quality of Control

Let us examine the effect on quality of control of using integral-action time $S = T$.

Fig. 7-2. Phase lag introduced into controller by integral action.

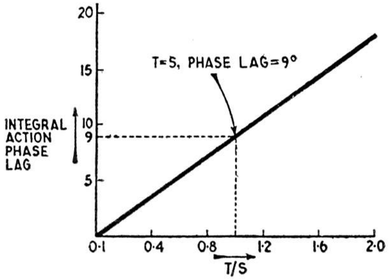

Fig. 7-2 shows that the phase lag due to integral action of this value is about 9 deg. The controller (proportional + integral) now has a total phase lag of 180 + 9 = 189 deg., and therefore "matches" a plant with a phase lag of 360 − 189 = 171 deg., instead of 180 deg. for proportional control alone.

To decrease the plant lag from 180 to 171 deg., the operating period must be increased. This in itself implies slower recovery after a disturbance. In addition, however, the plant attenuation (A) is decreased. Therefore controller gain, which must be made equal to A, must also be decreased. Fortunately, integral action at $S = T$ makes negligible contribution to controller gain[2], but since the gain has to be reduced, μ must be decreased. The deviation-reduction factor is thus decreased and the time for return to desired value is increased.

---

[2] The phase lag due to integral action is $\tan^{-1}(T/2\pi S)$. The contribution of integral action to controller gain can be shown to be $\sqrt{1 + (T/2\pi S)^2}$, *which for* $T/S = 1$ is 1.01.

It is, therefore, unwise to use integral action "because it is there and cannot do any harm." It can do harm; unless it is essential it should not be used without careful consideration. Much can be done by proper use of derivative action, as will be seen, to increase and decrease the proportional bandwidth; in many cases this will reduce offset to a tolerable value and make integral action unnecessary.

The seriousness of the effect of integral action on control quality depends on the extent to which operating period must be increased to obtain the required reduction in phase lag in the given plant, and how much the attenuation of the plant falls off as a consequence. These facts can be established from the frequency-response diagram of the plant.

A useful fact to remember is that integral action should be used, in general, only when the proportional band is so wide that expected load changes produce serious offset.

The shortest integral-action time (S) which can normally be used profitably is $S = T$, where T is the operating period for which the plant phase lag is 171 deg. for damped oscillations.

EQUATION FOR PROPORTIONAL PLUS INTEGRAL CONTROL

The output of the controller is the sum of the proportional and integral outputs, and the total potential correction Θ is the sum of the two potential corrections. Hence:

$$\Theta = -\mu\left(\theta + 1/S \int \theta\, dt\right) \qquad (3)$$

where the first term is the proportional-control action, and the second term is the integral-control action.

DERIVATIVE CONTROL

It has been shown that integral action is not desirable if it can be avoided because it leads to (1) the use of a wider proportional band, (2) slower return to desired value, and (3) less control of overshoot.

A common-sense approach to the problem suggests that overshoot can be reduced by an action which is proportional to the *rate of change of the deviation*. In this way a rapid departure from the desired value would be countered by a large corrective action, which would be brought into play as soon as the change commenced, and which would be reduced as the rate of change became less.

Such an action is available in proprietary makes of controller. It is called *derivative action*. Derivative control is defined (B.S.I. Definition 2414) as: "A type of control in which the potential correction is proportional to the rate at which the deviation changes." This definition can be stated in the equation:

$$\Theta = -\rho\, d\theta / dt = -\mu\, (R)\, d\theta/dt \qquad (4)$$

where ρ is the derivative-control factor, and R is the derivative-action time.

As for proportional and integral control actions, the derivative-control factor (ρ) is determined by the product K_2K_v, where K_2 is the derivative-action effect due to the controller, and K_v is the valve coefficient (assumed linear for small displacements. That is,

$$\rho = K_2K_v$$

The controller output due to derivative action is

$$V_D = -K_2\, d\theta/dt$$

Therefore $\Theta = K_vV_D = -K_vK_2\, d\theta/dt = -\rho d\theta/dt$

The derivative-control factor is not used in practice. As for integral control, the magnitude of derivative action is defined as a time (R) in terms of the proportional action of the controller. The *derivative action time* (R) is defined (B.S.I. definition 2504) as: "The time interval in which the proportional action increases by an amount equal to the derivative action when the deviation is changing at a constant rate."

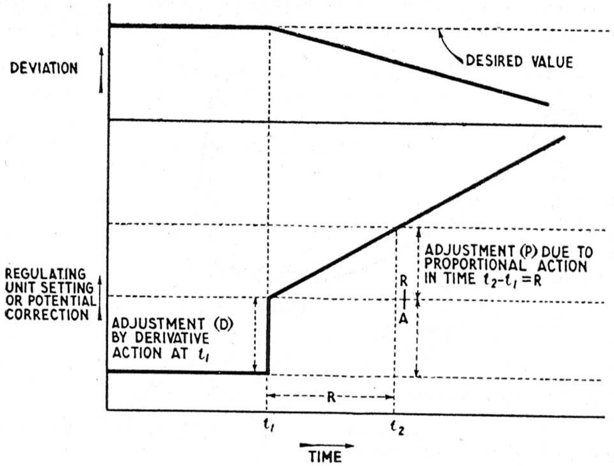

Fig. 7-3. Derivative action following a deviation change of constant rate.

Fig. 7-3 shows the effect of derivative action. Note that the full derivative action corresponding to any rate of change of θ, takes place immediately θ commences to change at this rate, and remains constant as long as the *rate of change* of θ remains constant.

As for integral action, the addition of derivative action to a proportional controller introduces a phase change. Integral action, we have seen, produces a phase *lag*, with consequent disadvantages; derivative action produces a phase *advance*, and from this derives its great value[3]. This phase advance depends on the derivative-action time and on the operating period. Phase advance is plotted against T/R in Fig. 7-4.

Derivative Action as a Means for Increasing μ

Quality of control improves as μ is increased. When proportional control is used alone, the value of μ is fixed by the attenuation in the plant at the natural period which gives 180 deg. phase lag. As the addition of integral action increases the controller phase-lag, a proportional + integral action controller must be matched to the plant at a longer period, which gives less phase lag. At this period the attenuation will be less and hence the value of μ will have to be less.

In order to be able to use an increased value of μ, it is necessary to work at a shorter period, for which the plant attenuation is greater. At this period there is also greater phase lag in the plant. The controller must therefore produce correspondingly less phase difference at this period.

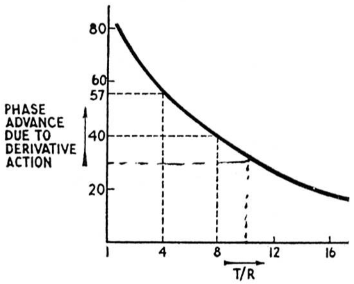

Fig. 7-4. Phase advance caused by derivative action.

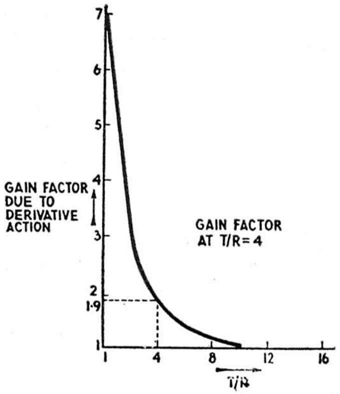

Fig. 7-5. Gain factor due to derivative action.

Unfortunately, derivative action makes a considerable contribution to controller gain[3], as can be seen from Fig. 7-5. This limits the amount of derivative action which can be used, as shown by the following example:

By adding derivative action, which produces a phase advance (Fig. 7-4) to a proportional controller, the phase lag of the controller can be reduced to less than 180 deg. For example, for a value of $T/R = 8$, the phase advance is 40 deg.

The controller phase lag is therefore $180-40 = 140$ deg.; the period (T) of the plant with characteristics plotted in Figs. 6-3 and 6-4, which gives a phase lag of 220 deg., is 10 minutes. The attenuation for $T = 10$ minutes is 20 and, therefore, to obtain sustained oscillation $\mu = A = 20$.

Note that with proportional control alone on this plant, sustained oscillation was given by $\mu = 10$; that is, by a proportional band twice as wide.

Once T is known, the required value of the derivative action time (R) is found from $T/R = 8$. In this instance $T = 10$, and hence $R = 1.25$ minutes.

Fig. 7-5 shows that the gain factor in this example, for which $T/R = 8$, is negligible.

If T/R is now taken as 4, the phase advance = 57 deg. (Fig. 7-4) and the gain factor = 1.9 (Fig. 7-5).

Using Figs. 6-3 and 6-4, the period which gives plant phase lag of 237 deg. is 7.5 minutes; the attenuation at this period is 27. The total controller gain must therefore be 27 (to give continuous oscillation), and as we have a gain factor of 1.9 due to the derivative action, $\mu = 27/1.9 = 13.5$. At period 7.5 minutes, $T/R = 4$ gives $R = 1.9$ minutes.

In this example we have increased the over-all gain of the controller to 27, but we have reduced μ to 13.5; however, the period has been reduced to 7.5 minutes. It is clear that the derivative action time must be chosen to give the best control according to the conditions and requirements.

To find μ for e/1 damping with proportional plus derivative action, the same procedure is applicable as for undamped oscillation, but the 10-percent addition to the phase lag must be made in the frequency-response diagram. The dotted curve in Fig. 7-5 must therefore be used.

The important points regarding use of derivative action are: (i) It permits the use of a higher μ and narrower proportional band than would be possible with proportional control alone; (ii) it will, by permitting a higher μ, assist in reducing offset; (iii) it will, from its primary function, reduce peaks due to rapid changes in conditions; and (iv) as the derivative-action time R is increased, a limit is reached at which any further increase in R leads to worse control. Instability becomes evident and increases rapidly with any increase in R. The reason for this is apparent because the over-all gain is now too high and the oscillations are being amplified instead of being reduced. When used correctly, derivative action is a stabilizing factor in control.

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[3] Phase advance due to derivative action is $\tan^{-1}(2\pi R/T)$, where R is the derivative-action time, and T is the operating period. The additional gain produced by derivative action is given by the factor $\sqrt{1 + (2\pi R/T)^2}$.

Equation for Proportional plus Derivative Control

The output of the controller is the sum of the proportional and derivative outputs, and the total potential correction (Θ) is the sum of the two potential corrections:

$$\Theta = -\mu\ (\theta + R\ d\theta/dt) \tag{5}$$

Proportional plus Integral plus Derivative Control

The equation for a controller with the three basic control actions is:

$$\Theta = -\mu\ (\theta + 1/S \int \theta dt + R\ d\theta/dt) \tag{6}$$

The factors μ, S, and R are not independent in many pneumatic controllers. Hence, if the settings are made on the controller (and the dials are correctly calibrated in R and S for independent action) the *effective* values of derivative and integral action times will not be as set. The practical significance of this fact will be considered in the next installment, which will deal with the principles of operation of typical pneumatic controllers with proportional, integral, and derivative action. Some practical suggestions will also be made for setting up such controllers on the plant.

CHAPTER VIII

PNEUMATIC-CONTROL TECHNIQUE

Most controllers now in use in chemical and other process industries are operated pneumatically. However, the "all-electric" or "all-electronic" controller is becoming a successful rival.

The reasons for the popularity of air-operated equipment are discussed briefly. It will be seen that modern electrical and electronic technique can provide a good answer to each of these reasons except one—there is no electrical rival to the air-operated diaphragm control valve. However, an electrically operated valve based on a completely new design does seem at last to be a probability rather than a desirable possibility.

Reasons for Popularity of Pneumatic Controllers

Flameproof Requirements

The cradle of automatic control was the American oil industry, and one of the first requirements of equipment developed for the oil industry was safety against fire and explosion hazards in the refinery. It was natural, therefore, that pneumatic, hydraulic, or mechanically operated instruments should be developed by instrument manufacturers who were anxious to supply the demand. Once the initial impetus was given along these lines, installation of pneumatic equipment became orthodox practice. Perhaps the manufacturers of electric and electronic equipment would have had more success if they had realized how many plant control problems can be solved by using narrow-band proportional control without integral-control action. However, today the "all-electric" controllers offer advantages in performances and can satisfy flameproofing requirements.

Ease of Generation of Control Actions

Although proportional action is easily obtained electrically, it has been more difficult to generate integral action with the long time-constants (of the order of minutes up to half an hour), which are required for process work.

Equation for Proportional plus Derivative Control

The output of the controller is the sum of the proportional and derivative outputs, and the total potential correction (Θ) is the sum of the two potential corrections:

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Reasons for Popularity of Pneumatic Controllers

Flameproof Requirements

The cradle of automatic control was the American oil industry, and one of the first requirements of equipment developed for the oil industry was safety against fire and explosion hazards in the refinery. It was natural, therefore, that pneumatic, hydraulic, or mechanically operated instruments should be developed by instrument manufacturers who were anxious to supply the demand. Once the initial impetus was given along these lines, installation of pneumatic equipment became orthodox practice. Perhaps the manufacturers of electric and electronic equipment would have had more success if they had realized how many plant control problems can be solved by using narrow-band proportional control without integral-control action. However, today the "all-electric" controllers offer advantages in performances and can satisfy flameproofing requirements.

Ease of Generation of Control Actions

Although proportional action is easily obtained electrically, it has been more difficult to generate integral action with the long time-constants (of the order of minutes up to half an hour), which are required for process work.

Pneumatic operation, however, has provided a simple and economical means of generating integral action.

Derivative action, which was introduced much more recently, is again a simple matter to produce by pneumatic arrangements. It was, therefore, added to existing proportional plus integral controllers without difficulty.

Advances in application technique, and requirements for more and more precision in control, have made increasing demands for stability of calibration of the integral and derivative units. The best equipment has been able to keep pace with the demand by careful attention to the design and manufacture of the "restrictors"; however, the provision of precision and stability should be easier to provide in electrical equipment, now that improvements in electrical components (particularly capacitors) and techniques have made the design of all-electrical controllers (with proportional plus integral plus derivative control actions) a practical possibility. In America and in Europe, "all-electronic" three-action controllers are now operating successfully.

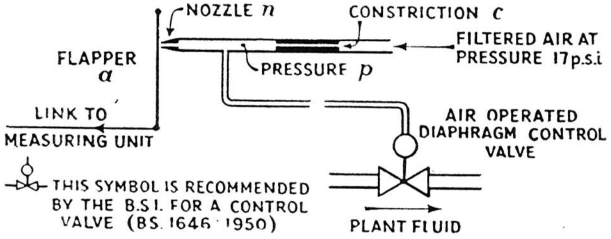

Fig. 8-1. Basic flapper/nozzle system.

Simplicity and Low Maintenance

Air-operated controllers are simple in construction and are cheap to maintain, given reasonable operating conditions. There is little to go wrong provided the controller is made well and supplied with clean air during its working life. The risk of interference by dirt and attack by corrosive atmospheres is automatically minimized by the constant air bleed from the controller itself, which is thus purged continuously with clean air.

The amount of air used by a controller varies from one proprietary instrument to another, but is usually between 0.2 and 0.5 cu. ft. per min. In a large plant where large air compressors are required for other services, the cost of such air per controller might be as low as $10 per annum.

Control Valve

The reliability and low maintenance cost of the air-operated diaphragm valve, coupled with its comparatively low initial cost, make it an obvious choice until a completely-new electrically-operated valve which is made competitive on all counts is developed. The simplicity and efficiency of the diaphragm valve has done much to popularize not only pneumatic controllers but automatic control itself.

The Future Trend

For many years to come, the pneumatic controller will retain its popularity. However, only those makers will hold their ground who meet the requirements made necessary by the increasing need for precision control. This need demands calibrated setting dials for the integral and derivation action times, and stable retention of the calibration over long periods in use.

GENERATING CONTROL ACTIONS IN PNEUMATIC CONTROLLERS

Many engineers and managers of chemical plant must often wonder why controllers vary widely in cost, or why there is a basic difference between a wide-band proportional controller and a narrow-band controller. The basic design principles provide the answer to these questions.

TWO-POSITION CONTROL ACTION

The basic principle employed in most controllers, whatever action they generate, is shown in Fig. 8-1. Filtered air is fed into the system at constant pressure. It flows through constriction C to nozzle N, from which it escapes to atmosphere at a rate depending on the position of plate A. This plate is called the "flapper," "baffle," or "vane."

The constriction C is smaller than the constriction in the nozzle and hence gives a greater pressure drop than the nozzle. Suppose C gives a four times greater pressure drop than does N. Then, if the flapper A is too far from N to affect the flow, and the constant-pressure air supply is at 20 psi., the pressure p will be 4 psi.

If A is now moved up to N so that it completely closes the nozzle, pressure p rises to 20 psi. If A is now moved slowly away from N, the pressure p drops again to 4 psi. after a small movement of A. This movement has generally been considered to be of the order of 0.002 inch; recent measurements made on a widely used controller showed that the movement was ¼ of 0.001 in.

This system can change pressure p from 4 to 20 psi. when the position of A relative to N is changed by as little as 0.002 in. Therefore, by pivoting *A* at a fixed point *F* and linking it to a measuring unit, a sensitive two-position (or on/off) control action is obtained.

NEED FOR A RELAY VALVE

The performance of this simple system is limited severely by the slow rate at which pressure *p* changes when *A* moves to a new position—if the regulating unit (and the line to it) has considerable capacity. Table 1 shows the time lag for this system used with a typical control valve. The rate of increase of *p* is limited by the rate at which the supply air flows through the constriction *C*; the rate of decrease is limited by the rate of air leakage to atmosphere through *N*.

The diameter of *N* must be made small so that the force exerted on *A* by the jet of air from *N* is negligibly small compared to the working force available to deflect the measuring-unit pointer or pen arm. This is particularly important when the measuring unit is a deflectional one, such as a milliammeter or a gas-filled thermometer. When it is servo operated (e.g., a self-balancing potentiometer) the working force available to position the flapper is larger and the "jet pressure" permissible is correspondingly greater.

Most makers, however, make one standard control unit to operate from all types of measuring unit, and the nozzle is therefore made as fine as practicable. The lower limit of nozzle and constriction diameters is set by the necessity of avoiding "blocking up" by the fine particles of dust, oil, or water which are not removed by the filters normally used. Precautions are necessary to obtain completely dry air, free of all oil and dust. In general, therefore, the nozzle diameter is of order 0.04 to 0.02 in.; that of *C* is two or three times smaller.

TABLE 1.—TIME LAG IN SECONDS DUE TO CAPACITANCE AND RESISTANCE OF CONNECTING TUBING AND REGULATING UNIT.

Diaphragm diameter, (*in.*)	*Length of 3/8-in.-O.D. copper tubing connecting controller to regulating unit*		
	1 ft.	500 ft.	500 ft. with positioner.*
16	1.4 sec.	8 sec.	3 sec.
12	1 sec.	4 sec.	2 sec.

*The effect of the positioner on lags with short connecting tubing is negligible; the positioner may still be required for accurate positioning of the regulating unit.

The small nozzle diameter ensures low jet-pressure on *A*, and hence negligible reaction on the measuring unit, and also reduces waste of air. On the other hand, it necessitates the use of a relay valve (Fig. 8-2) to provide rapid response.

Operation of Relay Valve

As seen from Fig. 8-2, if *p* decreases to minimum value, the bellows *B* contracts and moves valve *V*, so that air at supply pressure is transmitted to the regulating unit. If *p* increases to maximum value, valve *V* cuts off the supply air and allows the air under pressure in the regulating unit and connecting pipe to escape rapidly to atmosphere.

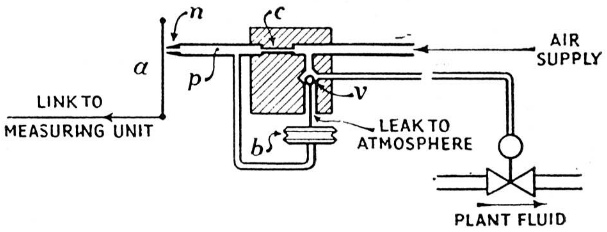

Fig. 8-2. Flapper/nozzle system with relay valve (continuous-bleed direct-action type).

As the output pressure decreases as *p* increases and vice versa, this relay valve is said to be "reverse acting." A "direct-acting" valve is shown in Fig. 8-3. Either valve can easily be modified to obtain the opposite action.

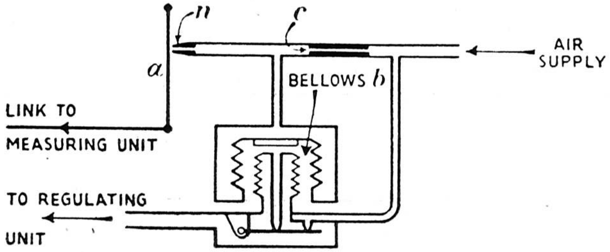

Fig. 8-3. Flapper/nozzle system with relay valve (non-bleed reverse-action type).

There is a basic difference between the two relay-valve designs, which is of importance when they are used with proportional controllers—the valve in Fig. 8-2 bleeds air to atmosphere from supply whenever it is not at one or other end of its travel; that in Fig. 8-3 does not waste air in this way and is called a "non-bleed" type.

Amplification, a Second Function of the Relay Valve

In addition to increasing the response speed of the system, the relay valve often is made to amplify the change in p. For example, in Fig. 8-2, bellows B can be made so that it moves valve V over its complete travel for a change of, say, 4 psi. Hence, if p changes from 4 psi. (its minimum value in the example chosen) to 8 psi., the controller output will change from 20 to 0 psi.

This means that the maximum jet pressure on flapper A is reduced, and also the change in jet pressure exerted throughout the range of movement of A is reduced. It also means that flapper A need not seal the nozzle in order to give maximum controller output pressure. Several controllers employ this property of the relay valve so that the working range of p is low, say, 6 or 8 psi.

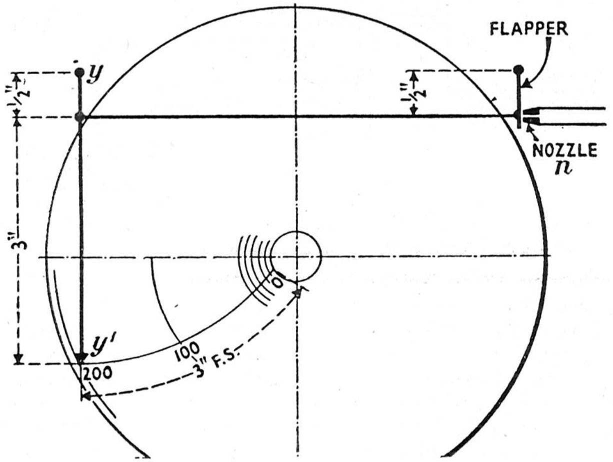

Fig. 8-4. Diagram of narrow-band proportional-controller linkage.

Narrow-band Proportional Action

When flapper A is moved away from nozzle N, the pressure p is proportional to the distance of A from N. Therefore, proportional action can be obtained from the system of Fig. 8-1.

Each value of the controlled condition (e.g., temperature) measured by the measuring unit corresponds to a unique position of the flapper A relative to the nozzle, and hence to a unique pressure p on the regulating unit. (It has been stated previously that this correspondence of each value of the flapper position to a definite controller output-pressure and regulating-unit setting explains offset due to load change.)

Note that the proportional action is obtained over a small movement of the flapper (say, 0.002 in.). Let us see what this high sensitivity leads to in a practical instance. In Fig. 8-4, YY' is the pen arm of a circular-chart temperature recorder/controller with range 0 to 200 deg C. and chart width of 3 in. If the dimensions of pen arm and flapper are as shown, a movement of 0.002 in. of the flapper will correspond to a pen movement of 0.47 percent of full scale, or 0.94 deg. C. Thus the proportional band-width of this recorder/controller is less than ½ percent, which is equivalent for practical purposes to two-position control.

In order to obtain a band-width of only 10 percent, the ratio of flapper movement to pen movement must be made 20 times smaller, giving an overall reduction ratio of 140. Such reductions can be constructed. Reductions of higher order, however, demand uneconomic precision in manufacture. Proportional band-width wider than about 10 percent is, therefore, usually obtained by a pneumatic feedback system, which presents an economic method of reducing the effective flapper movement per unit pen movement.

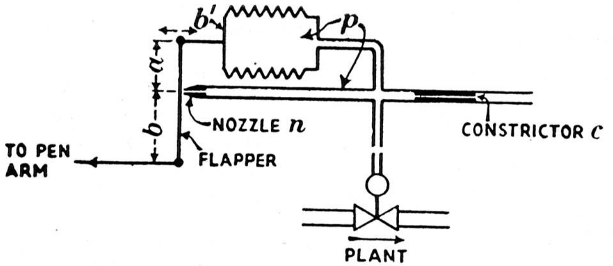

Fig. 8-5. Basic "feed-back" system of wide-band controller.

Wide-band Proportional Action

In Fig. 8-5, the simple system of Fig. 8-1 has been modified to give a wide proportional band. Bellows b' is connected pneumatically at its fixed end as shown; it is thus maintained at pressure p. The free end of the bellows carries an extension to which the flapper is pivoted.

If the pen arm moves to the right, p increases and b' expands. The upper end of the flapper is moved to the left. Hence the movement of the flapper opposite the nozzle is reduced; the desired decrease in "sensitivity" is thus provided. The extent of the decrease depends on (Fig. 8-5) the ratio of $a : b$ and the extension of bellows b' per unit change in p. Variation of either of these factors causes a change in the proportional band-width. In practice, the ratio $a : b$ is usually selected as the means of altering the band-width, as will be seen from the designs.

This "pneumatic feedback" system is simple and yet enables the flapper to be positioned with a precision of the order of millionths of an inch.

SETTING "DESIRED VALUE"

When the desired-value pointer and the pen arm are aligned together, the output of the controller in steady conditions should be 9 psi. (midpoint of the range 3 to 15 psi.). There is only one separation of flapper and nozzle which gives this output pressure. Hence the function of the "desired-value" setting arrangement is to provide that this separation exists when the controlled condition is at the desired value—i.e., when pointer and pen arm are aligned.

As both desired value and proportional band-width settings may be changed during operation, it is necessary to ensure that adjustment of one does not change adjustment of the other. This condition implies that change of band-width does not change flapper-nozzle separation at the mid-point of the band, and that change of desired value does not alter the ratio $a : b$.

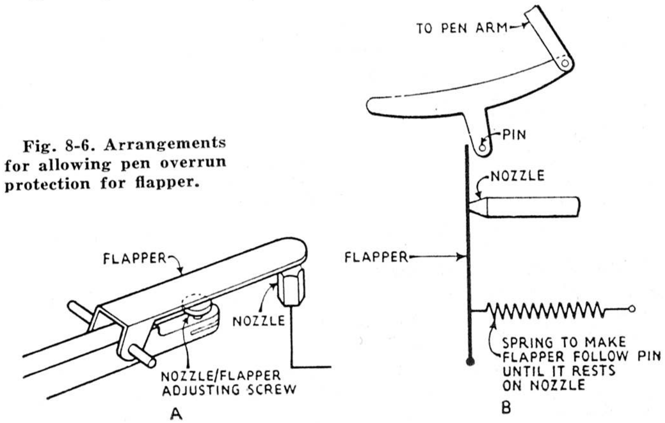

Fig. 8-6. Arrangements for allowing pen overrun protection for flapper.

The methods by which this is achieved are indicated for several types of controllers.

PROVISION FOR FREE MOTION OF PEN ARM

In Figs. 8-1 to 8-5, the pen is shown linked to the baffle. In practice, provision must be made for the pen arm to move freely beyond the point at which it has brought the flapper up to the nozzle face. Two devices for doing this are shown in Fig. 8-6.

Note that a restraining force keeps the flapper in contact with the arm pushing it. This force must either be small compared to the working force available to move the pen arm, or uniform throughout the range.

RANGE OF PROPORTIONAL BAND-WIDTH

With pneumatic feedback systems, proportional bands from 0 to 600 percent are available. Band-widths greater than 300 percent are seldom required.

It is advantageous to use the narrowest band-width compatible with stability of control. Offset cannot be greater than half the band-width, unless the regulating unit is inadequate, because the controller is giving either its minimum or maximum output at this value.

VALVE CHARACTERISTICS AND PROPORTIONAL CONTROL

The proportional controller gives an output pressure proportional to deviation from desired value, but proportional control will only be achieved if the regulating unit translates this proportional pressure into a proportional change of controlled variable. For example, a proportional controller operating an electric regulating unit to control temperature in an oven would not give truly proportional control if the regulator gave a linear relation between temperature deviation and electric current change—because the heating effect is proportional to the square of the current.

When controlling flow, it is generally an advantage to use a valve which gives equal-percentage changes in flow for equal changes in valve position through a wide range of valve movement. On the other hand, if large changes in demand are anticipated, it may be useful to employ a valve which gives increasing percentages of flow change for unit movement, on either side of the normal operating range.

It is always necessary to ensure that the pressure drop across the valve (compared to other pressure drops in the line) is the major factor in determining the flow rate. In general, the valve size must be less than the line size.

Any regulating unit must be chosen to give the safe position if air supply fails. It must close or open on air failure according to the plant requirements.

Consideration must be given to the use of a *valve positioner* to overcome "sticking" of the valve if the best control is required.

VALVE POSITIONER

The valve positioner (Fig. 8-7) is designed to apply the full air-supply pressure to the diaphragm until the valve position is accurately adjusted to that called for by the controller. It can be thought of as a two-position (or narrow-band-proportional) control unit, operating from a "measuring unit." The latter measures the difference between the actual valve position and that called for by the controller (as measured by the pressure output of the controller). The function of the control unit is to reduce this difference to zero. The result is that large forces are available to overcome any "sticking," particularly when small movements are required. A second purpose of the positioner is to make the valve movements more rapid (Table 1).

GENERATING PROPORTIONAL PLUS INTEGRAL ACTION

It has been shown that proportional control action alone gives a definite setting of the regulating unit for each value of the deviation within the control band, and that it is therefore impossible, by using proportional action alone, to restore the deviation to zero if any permanent change of either supply or demand occurs.

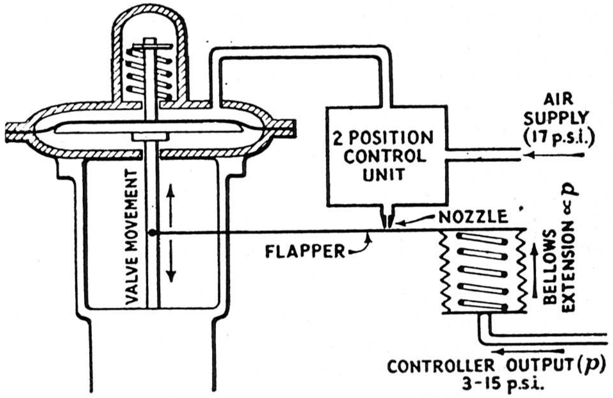

Fig. 8-7. Principle of valve positioner.

If a narrow proportional band is used, the offset due to any likely supply or demand changes may be small enough to be permissible without harm to the process. For example, if a 10 percent proportional band is used on a recorder/controller of range 100 deg C., the maximum offset possible (whatever the change in supply or demand) is ± 5 deg. C.* because at this value the controller output will be either 3 or 15 psi. and the regulating unit will be either full open or shut. In practice, the normal supply or demand changes in the system might not be large enough to give more than ± 1 C. degree.

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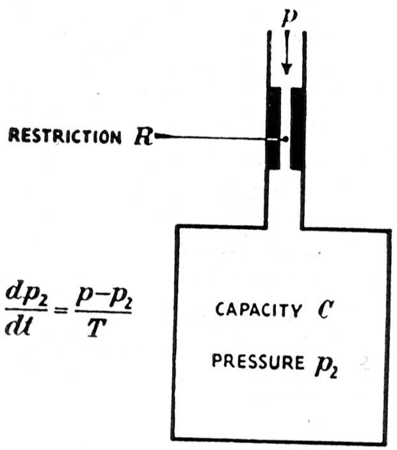
*Provided that the regulating unit is half open at the desired value, and that it is of sufficient capacity to deal with the largest changes in conditions which are encountered.

However, if the proportional band had to be increased from 10 to 50 percent, the offset would become ± 5 deg. C., and perhaps too great for satisfactory plant operation. In such circumstances integral action should be employed.

Integral action is designed to produce a correction which increases at a *rate* proportional to the deviation. In order to generate an action which increases at a rate proportional to θ, it is natural to use a system containing a capacity fed through a resistance. Fig. 8-8 shows a vessel of capacitance

Fig. 8-8. Method of generating integral action.



(or volume) C being fed with air at pressure p through a constriction having resistance R to air flow.

The *rate* at which p_2 changes depends directly on the pressure difference $p - p_2$ and inversely as the product of the resistance R and capacitance C.

$$dp_2/dt = (p - p_2)/CR = \triangle p/T \qquad (1)$$

If a proportional controller is operating steadily at desired value, the pressures on both sides of the restriction in Fig. 8-8 will be the same (p_2). Immediately following a sudden deviation (θ) in controlled condition, the output pressure (p) will change. The difference $p - p_2$, or $\triangle p$, will be proportional to θ. Therefore

$$dp_2/dt = \triangle p/T \propto \theta/T \qquad (2)$$

This, by definition, is integral action because the *rate* of controller action is proportional to the deviation, and hence the potential correction equals the integral of θdt. That is, $\Theta = (1/T) \int \theta \, dt$. Fig. 8-9 shows a controller mechanism for producing integral action (in addition to proportional and derivative actions). The capacity is a bellows which adds a component proportional to p_2 to the "sensitivity reduction" brought about by the "feed-back" bellows.

The integral contribution continues until θ is reduced to zero and is always proportional to p_2. Since p_2 is proportional to the integral of θdt, integral action builds up until $\theta = 0$, and its effect is inversely proportional to T, the time constant of the system.

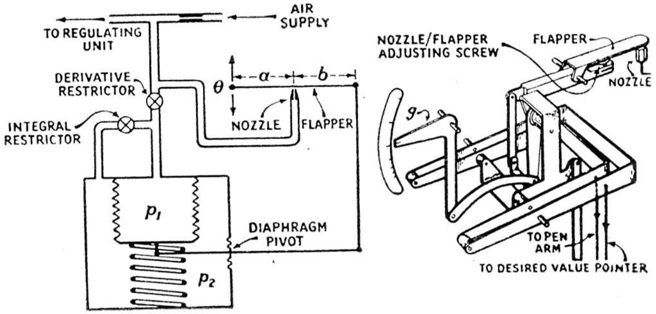


Fig. 8-9. Typical controller mechanism for proportional plus integral plus derivative actions. The control relay (Fig. 8-2) is not shown for simplicity—but would be placed immediately above the derivative restrictor at the entrance to the bellows unit. Note that the single bellows unit provides the three basic control actions. If the derivative restrictor were opened completely, and the integral restrictor closed, the bellows unit provides proportional control only.

INTEGRAL-ACTION TIME

The amount of integral action employed in a proportional plus integral action controller is defined in terms of a time S, which is proportional to T. It is called the integral-action time and it is used instead of T because it is easy to determine directly in terms of the proportional action.

By definition, the integral-action time is the time (S) taken for the integral action to increase by an amount equal to the proportional action *when the deviation* θ *is held constant.*

Since the potential correction due to proportional action is $\Theta_P = -\mu\,\theta$, the definition means that the integral action must be generated at such a rate that

$$\Theta_P = -\mu\,\theta = -\gamma \int^t \theta\, dt$$

$$= -\gamma\,\theta\,S \quad \text{(since } \theta \text{ is assumed}$$

constant for a time t equal to S).

Therefore $$\gamma = \mu/S$$

The contribution of integral action increases as S decreases. It has already been stated that usually the optimum value of S is that equal to the natural period of the plant. (See equation 6 of chapter 7 for the complete controller equation.)

GENERATING PROPORTIONAL PLUS DERIVATIVE ACTION

Derivative action must add a component to controller output which is proportional to the *rate* of change of deviation.

The resistance of a restrictor to air flow is again employed. The action is produced by decreasing the sensitivity reduction due to the "feed-back" system; i.e., the sensitivity of the flapper/nozzle system is increased.

The output pressure p of the controller (Fig. 8-9) is applied to the feed-back bellows through the "derivative restrictor." A sudden change in p due to a change in deviation θ will therefore not be transmitted immediately to the bellows. Consequently the bellows will be delayed in counteracting the flapper movement produced by the measuring unit. Hence the sensitivity of the system will be increased while θ is changing. The faster the change in θ, the greater the effect. The effect is proportional to the *rate* of change of θ.

The contribution of the derivative action depends on the restrictor resistance and the "feed-back" bellows capacity. As for integral action, it depends on the time constant of the system. Derivative action will, however, increase as the time constant increases.

Derivative action is defined as the time R taken to increase the proportional action contribution to controller output by an amount equal to the derivative action contribution when the deviation θ is changing at a constant rate.

To find the relation between ρ and μ, suppose the pen of the recorder/controller with proportional and derivative actions starts to move at constant rate across the chart, so that after a time R it has moved a distance θ. Immediately this change commenced, the derivative action would have produced a potential correction (Θ_D) proportional to the rate of change of θ, and equal to $\rho d\theta/dt$. If R is the time required for the proportional action to produce a potential correction (Θ_P) equal to the derivative action, clearly we must have

$$\Theta_D = \Theta_P$$

$$\rho\, d\theta/dt = \mu\,\theta$$

But $$d\theta/dt = \theta/R$$

Therefore, $\rho = \mu R$. (See equation 6 of chapter 7 for the complete controller equation.)

The value of the derivative time R is normally varied by changing the restrictor resistance; the effect of the derivative action increases as the restrictor resistance increases.

PROPORTIONAL PLUS INTEGRAL PLUS DERIVATIVE ACTION

It is sometimes necessary to use the three actions in one controller (although not as frequently as current practice indicates). A number of different methods of generating and combining the three actions are in use. The integral action usually is based on a restrictor plus capacity, and the derivative action on a restrictor between the output pressure and the "feed-back" bellows.

The methods of combining the actions determine the basic characteristics of the controller. Many proprietary designs of pneumatic controllers have the derivative and integral actions arranged either in "parallel" or in "series." It is profitable to select controllers on the basis of reliability, ease of setting up, adjustment, maintenance, robustness, and cost. Under ease of adjustment is included the provision of calibrated dials for setting integral and derivative action times, and restrictors which will ensure that these times are reproducible.

EFFECT OF USING BOTH DERIVATIVE AND INTEGRAL ACTIONS

When integral and derivative actions are both incorporated with proportional action, the generating systems interact in all the controllers used widely at present. The interaction, produced because the same bellows is used to obtain the derivative and integral actions, causes the action times generated to differ from those marked on the dials.

Also, it will be found that the proportional-control factor has apparently increased if the controller is used first without either integral or derivative actions, and then with both. (This increase is independent of period and must not be confused with the increase in "gain" due to the integral and derivative actions.

The change in the effective proportional-control factor is important. If not appreciated, it may be difficult to bring a plant under satisfactory control when all three actions are used. Increase of derivative action may well cause such a large increase in the proportional control factor (i.e., narrow the band-width so much) that the system will become unstable and go into violent oscillation. It is possible to increase the effective value of μ by a factor of 3 or more by changing the ratio R/S by, say, 2. This is not by any means an unlikely change to make in the integral plus derivative dial settings when a controller is being put into commission.

The interaction of the actions which results in a change of the integral and derivative times is of practical as well as theoretical interest. In particular it limits the ratio of the values of the integral and derivative times which can be obtained. Therefore the amount of derivative action, and hence the valuable phase advance, obtainable is limited.

The interaction produces "effective action" times (R and S) which differ from the "nominal" times (r and s) actually set on the calibrated dials. For the controller of the type shown in Fig. 8-9, it can be shown that

$$R = r/(1 + 2\ r/s)$$

and

$$S = s\ (1 + 2\ r/s)$$

The factor $(1 + 2\ r/s)$ is called the interaction factor.

CONSEQUENCES OF INTERACTION

(1) In some control problems it is necessary to use the three actions together and to employ the maximum amount of derivative action in order to obtain maximum phase advance from the controller and so work at the shortest operating period. The effect of interaction between the actions is to limit the maximum derivative action which can be *obtained* from the controller. This can be seen as follows, taking as an example the controller whose performance is defined by the equations above.

From these equations:

$$R/S = [r/s][1/(1 + 2\ r/s]^2$$

This expression has maximum value when $r/s = \frac{1}{2}$, or $R/S = \frac{1}{8}$. Thus the *effective* derivative-action time can never be more than one eighth of the effective integral-action time, which itself is often set equal to the plant period.

(2) The interaction factor also increases the proportional-action factor. Allowance must be made for this increase when adjusting a controller, or instability may result. For example, if $r = s/2$, the factor is 2; the effective proportional band-width will be halved.

Again, if an adustment is made subsequently to the derivative time, so that $r = s$, the effective band-width would be only one-third of the set width. This change in band-width might lead to instability in the control system, although not materially changing R/S. It is, therefore, important to be aware of this effect when setting up a three-action controller.

(3) Another implication of interaction is that any change in action times from their nominal values during operation, not only leads to a change in both action times, but also in effective proportional band-width. Such changes occur because the restrictors alter their resistance owing to mechanical changes or entry of dirt.

Note that the interaction factor depends on the arrangement for the addition of the output of the proportional, integral, and derivative units; therefore, each arrangement leads to a different interaction factor. The factor $(1 + 2\ r/s)$ applies only to controllers using the basic arrangement shown in Fig. 8-9.

CHAPTER IX

PNEUMATIC CONTROLLERS

In the concluding chapters, it is proposed to clarify and give point to the general theoretical discussion of the previous chapters, by describing some widely-used commercially-available control systems, and by giving some guidance for their use. Typical pneumatic and hydraulic controllers of American and British make will be presented.

ASKANIA REGULATOR CO.

"Jet-Pipe Regulator"

Key element of this regulator is the Jet-Pipe Relay (Fig. 9-1), which is functionally similar to a four-way valve. A pivoted stainless-steel tube is free to move, nearly frictionlessly, through a small horizontal angle. A fluid (oil or compressed air) is discharged at high velocity from the jet-pipe tip, and impinges on a plate containing two adjacent orifices, connected to opposite ends of a double-acting cylinder.

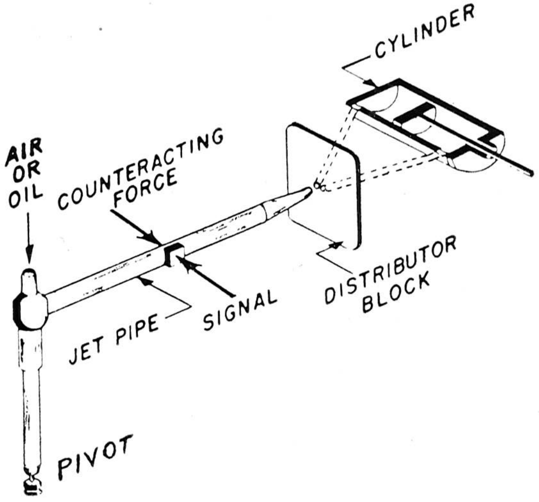


Fig. 9-1. Principle of the Askania jet-pipe relay.

When the jet pipe is centered between the two orifices, the pressures recovered are equal in both orifices and at opposite ends of the cylinder; and the piston is stationary. If the jet pipe is deflected toward one of the orifices and away from the other, by the motion of a diaphragm or other measuring device (see Fig. 9-2), a pressure difference is set up at opposite ends of the cylinder and the piston moves to effect control. The pressure difference set up at the cylinder is a direct function of jet-pipe displacement.

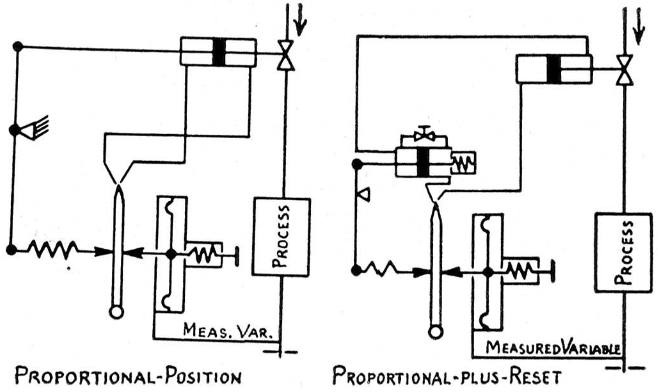


Fig. 9-2. Methods for obtaining proportional and integral control actions.

Thus, piston speed is a direct function of the amount of error. This is "proportional-speed floating control," which is a type of integral control action.

By the addition of mechanical or electrical feedback devices, this basic system can include the characteristics of proportional-position and proportional-plus-integral control. In Fig. 9-2, mechanical arrangements are shown for obtaining proportional and integral control actions. The left-hand diagram shows how a signal representing valve position is fed back in opposition to the error signal; in the right-hand diagram the direct feedback link between valve position and jet pipe is replaced by what amounts to a positive-displacement meter: a by-passed piston in series with the controlling piston.

It must not be assumed that all jet-pipe relays require considerable force (say nearly one ounce) to overcome frictions for accurate positioning. That friction has been minimized in some models is evident from the fact that one pneumatic model brought out about 1929 for furnace temperature control had a radiation-pyrometer primary element: the jet pipe was positioned by a permanent-magnet moving-coil mechanism. A modern version utilizes this same principle.

BAILEY METER CO.

The Bailey "Mini-Line" pneumatic control system is shown in Fig. 9-3 as applied to pressure control. It comprises a pressure transmitter, a "Mini-Line" relay, a hand-automatic selector, and a power unit. The transmitter establishes a pneumatic signal proportional to the measured variable. This signal is applied to a remote indicator, a remote recorder, and the "Mini-Line" relay.

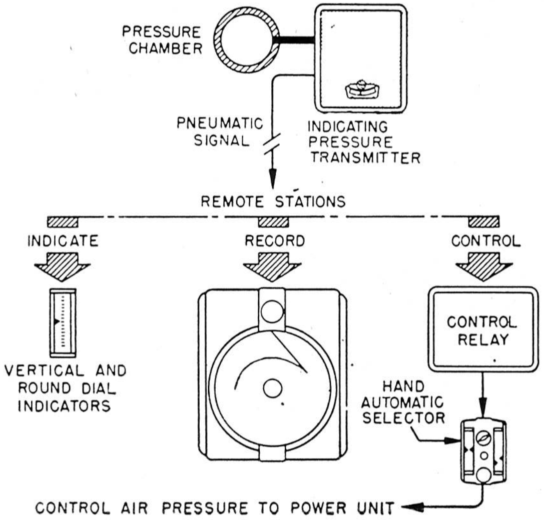


Fig. 9-3. Bailey "Mini-Line" control system.

This relay (Fig. 9-4) is used to generate proportional, derivative, integral and floating control actions as required. It also provides for remote desired-value adjustment from a manually-operated relay on the selector valve. This ratio relay may be calibrated for air pressure signal ranges of 3-27, 3-15, and 5-25 psig. It may be set either for proportional-position action or for proportional plus integral action by means of a selector switch.

The selector valve provides all necessary indications and control knobs for automatic or hand operation of the system. The standard selector includes four indications of air pressures pertaining to the control-system operation, a transfer switch for rapid change to either automatic or hand control, a desired-value or bias control adjustment depending upon system requirements, and a hand control knob for remote manual control. Automatic-manual transfer is made without "bumping" the controlled process.

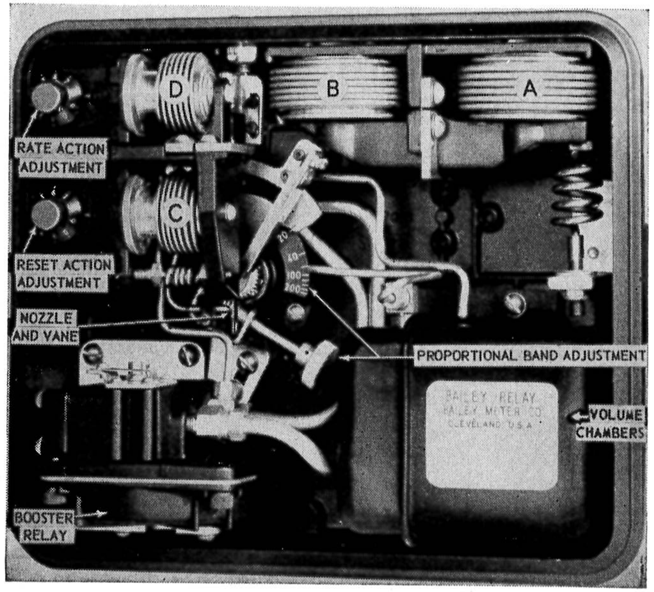


Fig. 9-4. Control unit for proportional, rate, reset and floating control actions.

THE BRISTOL CO.

Principal feature of the Bristol pneumatic controllers is the "free vane" first-stage amplifier. A second noteworthy feature is the unusual manner of generating integral action. Proportional action is generated as shown in Fig. 9-5. Immediately the leading edge of the vane enters the space between the two nozzles, the nozzle pressure is increased. Subsequent movements of the vane give proportional increases in nozzle pressure, just as in the flapper-and-nozzle system. The two nozzles are opposed, so that the vane suffers no reaction.

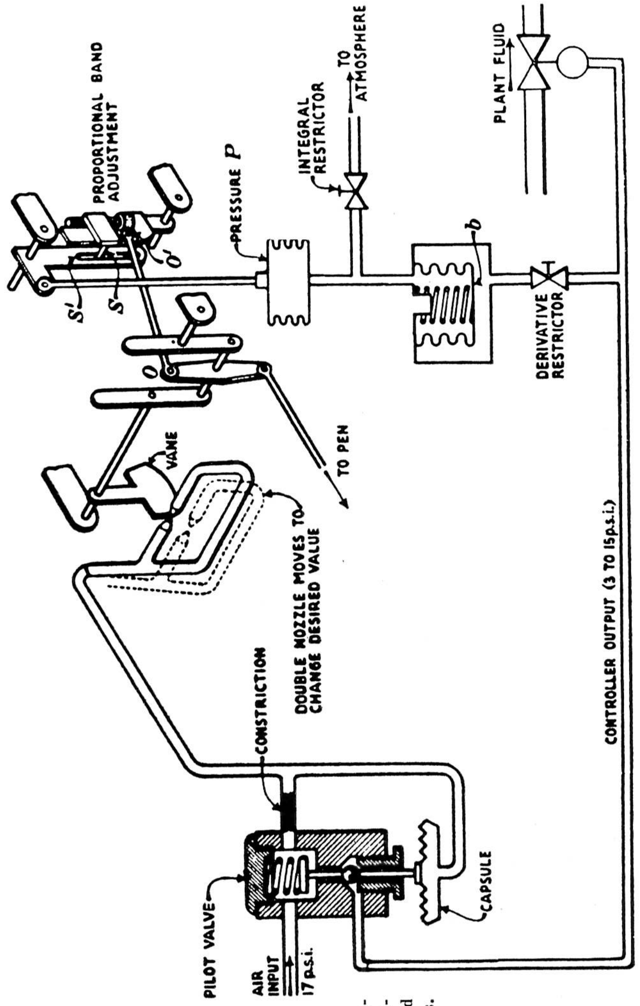


Fig. 9-5. Bristol "free-vane" controller for proportional, integral, and derivative control actions.

Wide-band proportional action is obtained as shown in Fig. 9-5. The band width is adjusted by altering the position of spigot s in slot s^1. The action is reversed by reversing the link carrying slot s^1 and moving the vane, so that the opposite leading edge is operative.

The desired value is set by rotating the double nozzle system as indicated in the figures.

Integral action is generated as follows: The output pressure of the controller is applied to the outside of bellows b. If the integral action restrictor is shut, changes in output pressure are simply transmitted to the feedback bellows, to give wide-band proportional action. But if the restrictor is open, air will leak to atmosphere and the pressure in the two bellows will change at a rate proportional to the time constant of restrictor plus bellows. Hence the consequent rate of movement of the proportional bellows will add integral action to the proportional action.

Derivative action is given by the restrictor between controller output pressure and the lower bellows.

The interaction factor for this design is $[1 + (r/s)]$ and the most powerful derivative action is obtained when the nominal derivative action time (r) is equal to the nominal integral action time (s); the interaction factor then is 2.

Note that when $r = s$ (and $R = \frac{1}{4}S$) the phase gain in this controller has the high value of 55 degrees when $s = \frac{1}{2}$ operating period.

FISCHER & PORTER CO.

An exception—the use of an outside-view photograph (Fig. 9-6)—is here made to show the Fischer & Porter Co. "P-4 Pneumatrol" because the Lucite-case model reveals some components of one of the various "stack" designs of "blind" (non-indicating) controllers brought out by several American instrument makers.

"Blind" controllers appeared a few years ago in large American chemical and oil companies where central control rooms are hundreds of feet away from the processing units. In order to minimize distance-velocity lags, each controller was installed close to the point of measurement and to the controlled valve, damper, or other final element. This did away with the most serious dead times.

In the unit shown in Fig. 9-6, the "stack" design makes it possible to obtain an increasing complexity of control ac-

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*The letters r and s are used throughout this chapter for the derivative and integral times corresponding to the *settings* on the respective restrictor scales; i.e. r and s are the nominal action times.

tions—in six stages from two-position to wide-band proportional with integral and derivative—by adding standardized parts.

An unusual feature of the unit shown in Fig. 9-6 is that it is a motion-input controller—as are most "instrument" controllers—rather than a force-input controller as are most "blind" controllers. This unit, however, is designed both for "case" mounting and for "field" (point-of-measurement) mounting. Note the plug-in air ports.

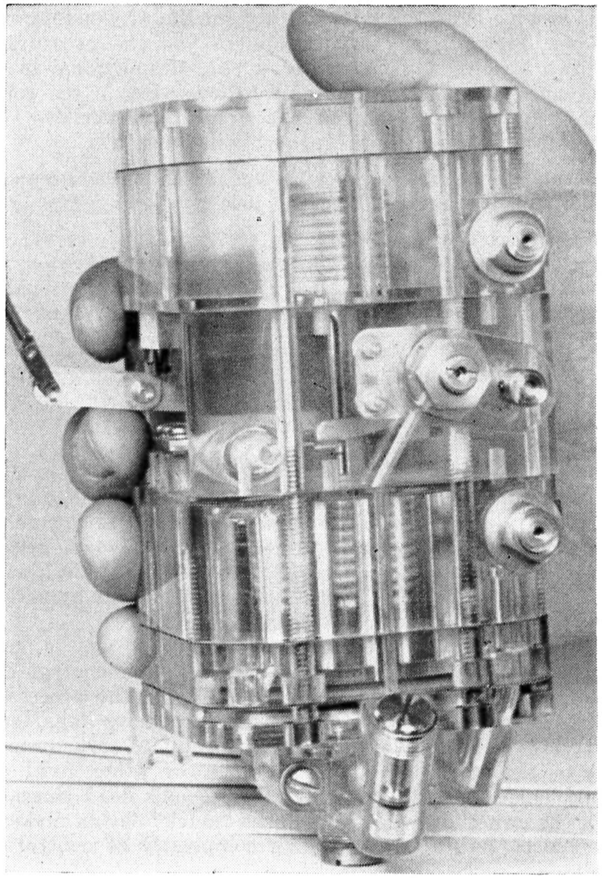


Fig. 9-6. Fischer & Porter "P-4 Pneumatrol" stack-type controller.

Foxboro Co.

1. "*Model* 40" *with* "*Hyper-Reset*"

Distinctive features of this controller are: (1) the mechanism for altering the proportional band, (2) the Bourdon tubes for integral and derivative restrictors, and (3) the third bellows inside the "feedback action" bellows to give added stability in the presence of high-frequency disturbances.

The proportional band adjustment is made by rotating the entire flapper-nozzle system (Fig. 9-7). When PC is vertical, movements of L will affect the flapper position but movement of L′ will have no effect. In this position the controller would have effectively two-position action.

By rotating the flapper-nozzle system from this position through 90 degrees, the effect of feedback (movement of L′) will be gradually increased, i.e., the proportional band width will increase. There will be no effect on the desired value setting. The usual range of band-width supplied is 0.5 to 200 percent.

The integral and derivative action restrictors consist of Bourdon tubes whose cross-section, and hence resistance to air flow, is varied by adjusting the curvature of the tubes.

A unique feature is the small bellows fitted inside the "feedback" action bellows. Without this extra bellows, the controller design would be basically the same in principle as that which was analyzed in detail in the preceding chapter. Its purpose is to give added stability to the controller for high-frequency (short-period) disturbances. This it achieves by reducing the over-all gain of the controller at short

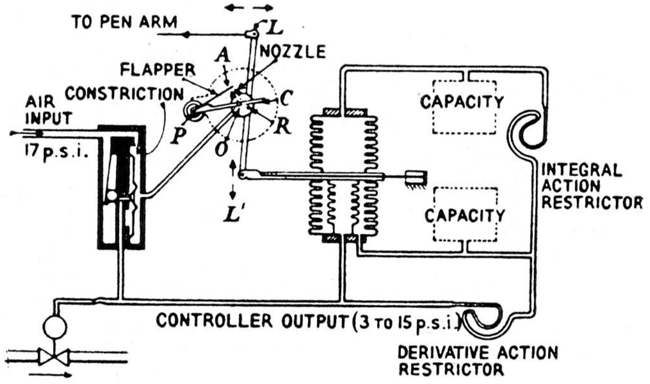


Fig. 9-7. Foxboro "Model 40" controller.

periods, with some sacrifice of phase advance at normal periods.

The interaction factor for this type of controller is more complex than for those previously described, i.e. $[1 + (5r/2s)]/[1 + (r/2s)]$. Hence, for the ratio $s = 2r$ recommended by the maker, the factor is 1.8.

The introduction of provision for increased stability in face of high-frequency disturbances reduces the phase advance obtainable—which for the recommended value of $r/s = \frac{1}{2}$, is about 15 degrees when the integral action time (s) set on the dial is about ½ (operating period).

2. *"Model* 58 *Consotrol"*

The principle of pneumatic transmission has made it possible to build pneumatic controllers of the force-balance type, sufficiently compact for graphic panel use. Such an instrument is the "Model 58" controller. Key element in this instrument is a unique force-balance mechanism. (Figs. 9-8 and 9-9) comprising four pressure-responsive metallic bellows positioning a free-floating disk about a fulcrum which is adjustable to produce any proportional band setting from zero to 500 percent.

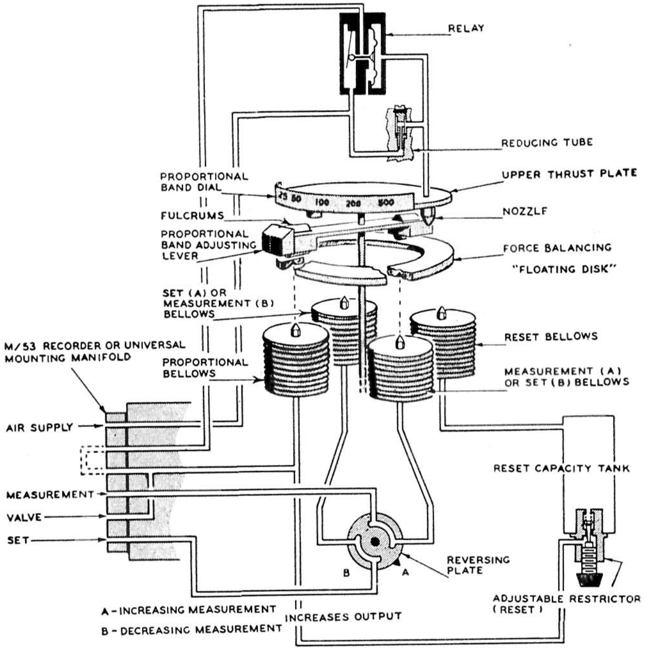


Fig. 9-8. Foxboro "Model 58 Consotrol" force-balance-type controller.

The floating disk acts as the force-balance detector and as the flapper of a conventional flapper-nozzle system, enabling relay output pressure to vary in response to changes in pressure in any of the four bellows.

Each of these bellows exerts an upward force on the disk. The net effect of all forces acting simultaneously establishes the horizontal position of the disk, its nearness to the nozzle and hence the output pressure.

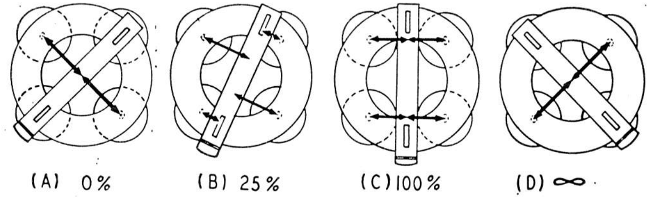


Fig. 9-9. Proportional-band adjustment on the "Model 58" floating disk.

In operation, any change in pressure in the measurement (or set) bellows slightly raises or lowers that side of the floating disk, causes a change in nozzle pressure which operates the relay to increase or decrease the output pressure. This pressure, acting on the proportional bellows, changes enough to restore the balance. Output pressure change is thus proportional to measurement (or set) pressure change.

If there is a sustained differential between set and measurement, a sustained difference between proportional and reset bellows pressures will result. But air will flow from one to the other, causing the disk to throttle the relay and change output pressure continuously to maintain this difference. This is integral control action.

The restriction between proportional and integral bellows is adjustable and hence integral-action rate is proportional to both the amount of restriction and to the deviation of measurement from desired-value or set point.

HAGAN CORPORATION

1. *Pneumatic Signal Transmitter*

Designed especially for use with the Hagan ring-balance flowmeter, the pneumatic signal transmitter (Fig. 9-10) is a position-balance nozzle-baffle proportional-action control unit whose output can be used to operate a diaphragm control valve or a remote indicator. Available maximum signal pressure ranges are 15, 30, and 60 psi. Proportional band is adjustable from 10 to 300 percent. The operation of the unit is evident from Fig. 9-10. Motion of the baffle causes change in pressure above the metallic diaphragm, which operates the relay valve to change the pressure in the main bellows. Pressure in the main bellows causes a vertical force that acts through the range spring to move the entire carriage assembly and cause it to pivot around the carriage pivot. This repositions the nozzle to give proportional action.

When the ratio pivot is at the extreme right, the feedback proportional-action motion is the greatest, the nozzle is repositioned the most, the controller has least sensitivity, and the proportional band is maximum (300 percent).

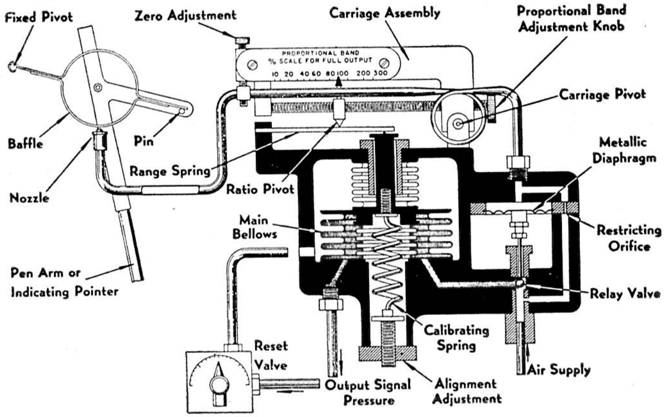


Fig. 9-10. Hagan pneumatic signal transmitter.

For controlling service, the transmitter can be supplied with integral action (as shown), remote adjustable set point, or derivative action.

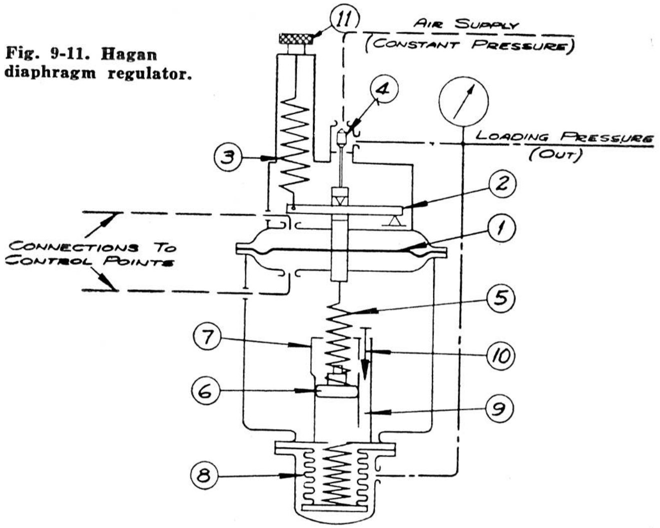
2. *Diaphragm Regulator*

For low-pressure or low-pressure-differential controlling service (inches water to about 3 psi.), the diaphragm regulator (Fig. 9-11) utilizes a diaphragm (1) and pivoted balance beam (2). Motion of the balance beam controls the escapement valve (4), which determines the output air signal. Proportional control action is obtained by a feedback bellows (8), which repositions the diaphragm and escapement valve. The repositioning motion operates through piston (6) in oil-filled cylinder (7) to give damped integral action. The amount of damping is controlled by valve (10) to suit the lag of the system under control.

3. *Ratio Totalizer*

Although called "ratio totalizer," this unit is a general-purpose control unit that gives not only proportional, integral and derivative actions, but also addition, subtraction, multiplication, and division actions. Hence it is both a control and a computer element. The input to the ratio totalizer is one or more signals from other signal transmitters—that is, it is a control element between pickup transmitter and final control element.

Fig. 9-11. Hagan diaphragm regulator.



The ratio totalizer (Fig. 9-12) is a pure force-balance unit in which the pilot valve controlling the output air pressure is positioned by the action of four nonmetallic diaphragms arranged in opposing pairs. The two elements of each pair are attached to a common post; a beam, rotating about a fulcrum, is connected between the two posts. The beam is positioned by the end posts; the left-hand post is positioned by input signals 1 and 2; the right-hand post is positioned by input signal 3 and the output signal 4.

The resultant force up or down at the left post multiplied by its distance to the fulcrum, or lever arm A (Fig. 9-12), always must equal resultant force at right-hand post multiplied by lever arm B. Hence moving the fulcrum to the right increases the effect of inputs 1 and 2 on the output; motion to the left has the opposite effect. This is the force-balance principle.

Owing to the force-balance principle:

(P4 — P3) (lever arm A) = (P1 — P2) (lever arm B)

Hence

$$P4 = (B/A)\ (P1 - P2) + P3$$

When A equals B:

$$P4 = P1 - P2 + P3$$

This makes possible the various actions of the unit, some of which are shown in Fig. 9-13. In 9-13,A, the difference between set-point and measured signals yields a proportional-action output signal. In 9-13,B, integral action is added to the proportional controller; this application is a clear illustration of the integral action of all pneumatic controllers. Similarly, the way derivative action is added (Fig. 9-13, C) is a clear illustration of a principle applicable to most pneumatic controllers. Fig. 9-13,D shows an averaging circuit—that is, P4 equals (P1 + P3)/2. Fig. 9-13,E shows a simple addition circuit. Fig. 9-13,F is a basic multiplier or divider circuit.

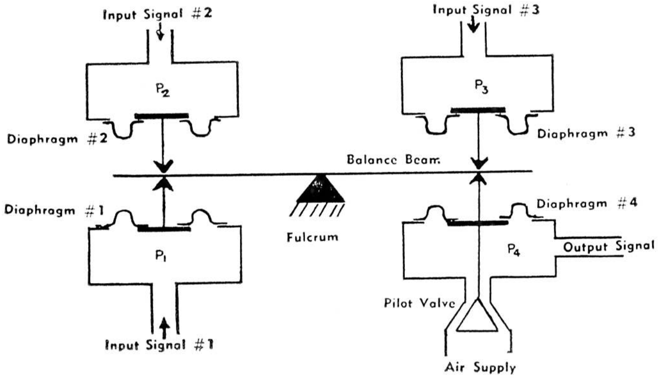


Fig. 9-12. Force-balance principle of ratio totalizer.

George Kent Ltd. (British)

"Mark XX"

The method of generating the actions was previously described (Fig. 8-9 in chapter 8) and is clear from Fig. 9-14. In the "Mark XX" controller, the characteristic feature of the relay valve is the double diaphragm system. When the nozzle pressure falls, the diaphragm system moves to the left and valve v leaves its seat s and closes at s^1. Air from the regulating unit thus bleeds to atmosphere, through the space between the two diaphragms, until p equals nozzle pressure. The reverse process happens when nozzle pressure rises. The valve is thus of the non-bleed

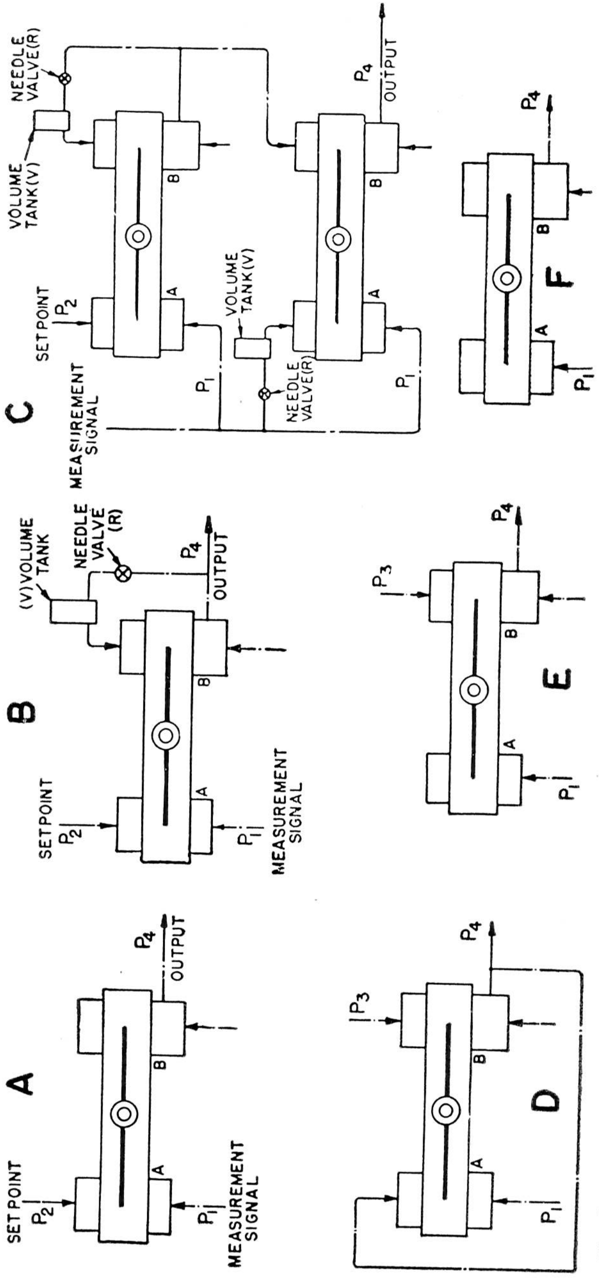


Fig. 9-13. Hagan ratio totalizer, showing A, use as proportional controller; B, proportional plus integral; C, proportional plus integral plus derivative; D, averaging; E, adding; F, multiplying

type and its amplification is unity, i.e. nozzle pressure is equal to controller output pressure.

Proportional band width adjustment is made by moving x (in the schematic diagram of Fig. 9-14) on the arc xyz.

The deviation is detected by a differential linkage (shown as differential lever mon in Fig. 9-14). It is clear that adjustment of the desired value will not alter the proportional

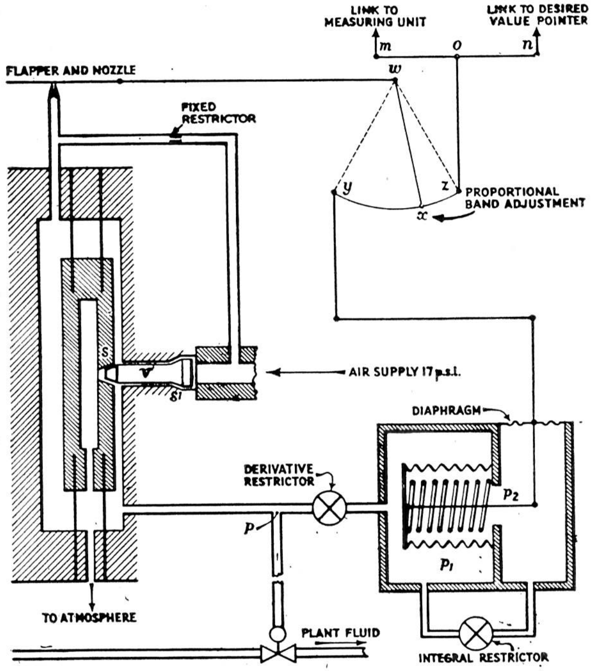


Fig. 9-14. George Kent "Model XX" controller.

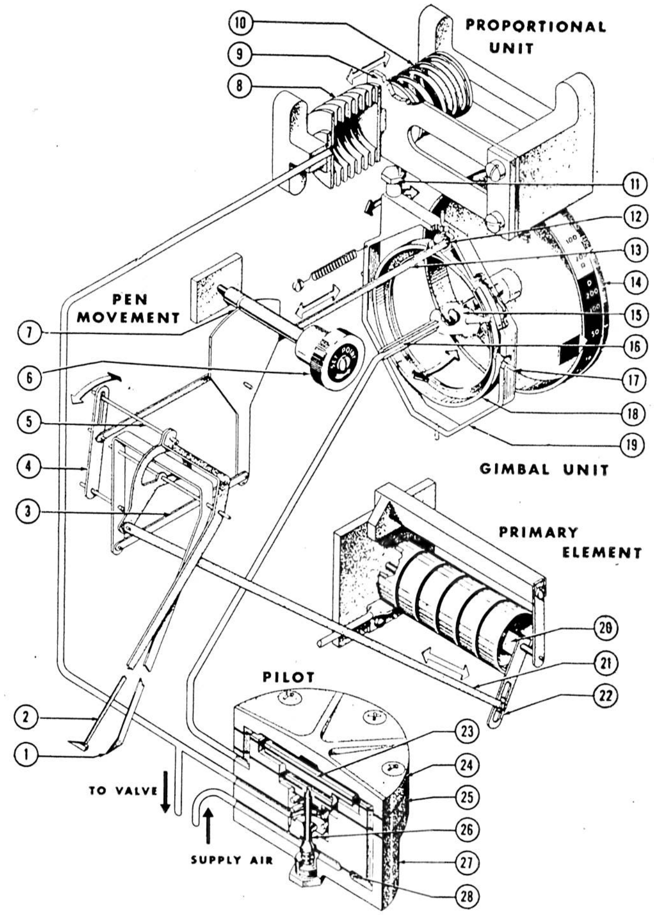
band width (i.e. the ratio yx : xz) if the system is perfectly constructed.

The interaction factor, as has already been shown in Chapter 8, is equal to $[1 + (2r/s)]$.

MASON-NEILAN REGULATOR CO.

"6000 *Series*" *Controllers*

Of the several distinctive features of these controllers, there may be singled out the "gimbal unit" which combines primary and "feedback" motions. This gimbal unit has the further advantage of making it possible to generate "differ-



1 Set point index
2 Pen
3 Index setting link
4 Control lever
5 Pen connector
6 Index setting knob
7 Friction drive
8 Proportional bellows
9 Proportional leaf spring
10 Proportional spring
11 Eccentric screw
12 Universal
13 Gimbal link
14 Proportional band wheel
15 Flapper
16 Nozzle
17 Pivots
18 Inner gimbal
19 Outer gimbal
20 Clamp
21 Element link
22 Take-off arm
23 Diaphragm block
24 End plate
25 Intermediate plate
26 Pilot plug
27 Pilot body
28 Metering tube (schematic)

Fig. 9-15. Mason-Neilan "6000 Series" controller for proportional action.

ential-gap action" in the same instrument with proportional action without change.

Fig. 9-15 is an instructional drawing of a "6000 Series" proportional-action controller. Proportional bellows 8, which is continuously connected to the output air, positions (through 9 and 11) outer gimbal 19 which pivots about the *vertical* axis. Inner gimbal 18 is suspended in the outer gimbal, by pivots 17, and rotates about a *horizontal* axis.

With flapper 15 in the quadrant as shown in Fig. 9-15, an increase in the controlled variable moves parts 22, 21, 4 and 13 so as to rotate inner gimbal 18 clockwise, causing flapper 15 to cover nozzle 16 and thereby increase output air pressure. (Action of parts 23-28 can be omitted.) The increase in output air pressure expands 8, rotating gimbal 19 about the vertical axis and causing flapper 15 to uncover nozzle 16. Since flapper movement for a 12-psi. change in output air is about 0.001 inch, this system is of the force-balance type. For any position of gimbal link 13 (i.e. any value of the controlled variable) there is only one possible position for proportional bellows 8.

Band-width adjustment: Rotating proportional band wheel 14 shifts the point of contact between the pin on flapper 15 and the bead on inner gimbal 18. This varies the amount of bellows movement required to compensate for movement of gimbal link 13. If the flapper is turned to a vertical position in line with universal joint 12, motion of the proportional bellows will have no effect on the flapper (i.e. minimum proportional band). Intermediate positions of the flapper will produce intermediate proportional bands.

On proportional-plus-integral controllers, the proportional unit is replaced by a "Reset Unit" whose construction differs by the addition of the integral bellows (in place of proportional spring 10 of Fig. 9-15), an adjustable resistance unit and a capacity.

MINNEAPOLIS-HONEYWELL REGULATOR CO.

"Air-O-Line" Controller

The Honeywell-Brown pneumatic controller employs a non-bleed-type relay valve. A second noteworthy feature is a liquid-filled bellows system to generate integral action.

The differential linkage between pen and feedback bellows and the adjustments for changing proportional band width are clear from the diagram, Fig. 9-16. A pressure proportional to the controller output pressure (p) is fed back, via the relay valve, into the case enclosing the right-hand bellows system. Suppose p decreases; then the spring at the left-hand end causes the whole bellows system to be

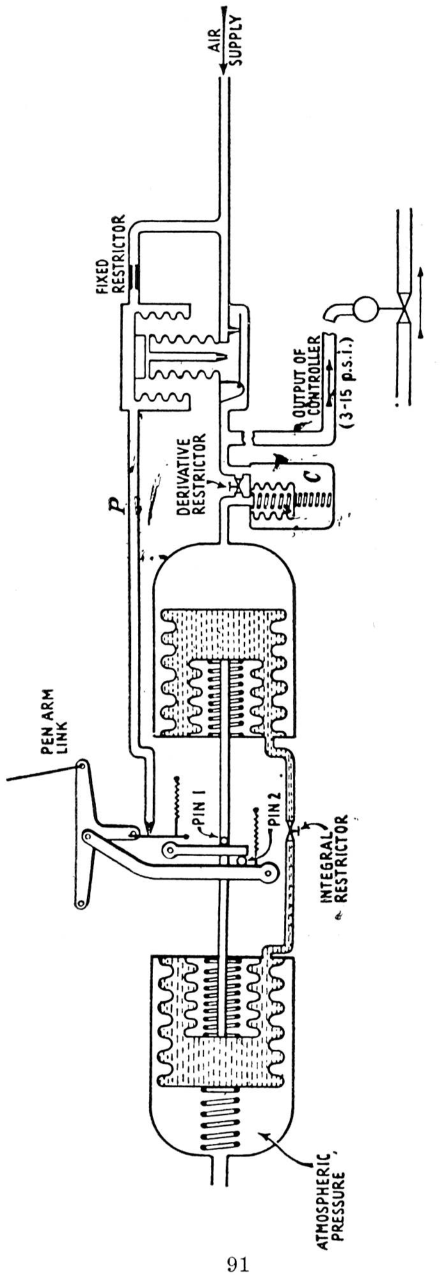


Fig. 9-16. Honeywell-Brown "Air-O-Line" pneumatic controller with non-bleed-type relay and liquid-filled integral-bellows system.

displaced to the right. The rod connecting the ends of the two inner bellows also moves to the right. This movement is proportional to the pressure change and it is transmitted to the differential linkage through pins 1 and 2. The separation of these pins determines the a : b ratio; pin 2 is adjustable; the usual range is 0.2-200 percent band width.

This proportional action is completed before any appreciable flow of liquid can take place through the restrictor, from one liquid-filled space to the other. The spring inside the inner bellows on the right-hand side has been extended, and therefore the liquid on this side will be at a lower pressure than that on the other, and the latter will tend to flow through the restrictor to the right-hand side. This flow causes the rod carrying pin 2 to tend to move towards its initial position at a rate depending on the output pressure change, i.e. on the deviation. Integral action is thus generated.

Derivative action is added by the derivative action restrictor. The effect of the associated capacity (C) and bellows unit is to limit the controller gain and phase advance at short periods; this characteristic would be useful when the plant suffered from rapid short-period random disturbances or the installation was exposed to vibration.

The theoretical equation for the controller shows that the interaction factor is $[1 + (r/s)]$. It does not permit derivation of a general relation between nominal and effective action times. The makers recommend that nominal derivative action time should be set at half nominal integral action time (i.e., $r = \frac{1}{2}s$). For this r/s ratio, the interaction factor is 1.5 and therefore the effective proportional band will be narrower, by this factor, than the nominal value set.

MOORE PRODUCTS CO.

"Nullmatic" Controllers

Mention has already been made of the introduction of "blind" controllers in order to minimize distance-velocity lags in large American plants with control rooms hundreds of feet from the processing units. Of these process-located controllers, the "Nullmatic" units were the first (1947) in which a stack of diaphragms and interchangeable parts were used in place of individual bellows-type components—all control actions being generated by balancing air pressures without use of pivots, linkages, or other parts subject to friction.

One of the "Nullmatic" controllers (the "Model 55") is shown schematically in Fig. 9-17. This model operates on the force-balance principle.

When the proportional-band needle valve is wide open, the band-width is minimal and the control action is practically two-position. When this needle valve is fully closed, a 200-percent band-width results from the 2:1 ratio of areas of the P_2 and P_3 chamber diaphragms.

"Reset" (integral) rate—i.e. the rate of change of P_8—is determined by the upper needle valve. The "reset reference" pressure P_4 is reproduced in the reset-pressure chamber through operation of a 1 : 1 relay. When the controller is not in balance, reset-reference pressure P_4 changes at a rate dependent on the setting of the reset needle valve. The pressure in the reference chamber is raised or lowered, producing the gradual change in P_8 necessary to rebalance the system.

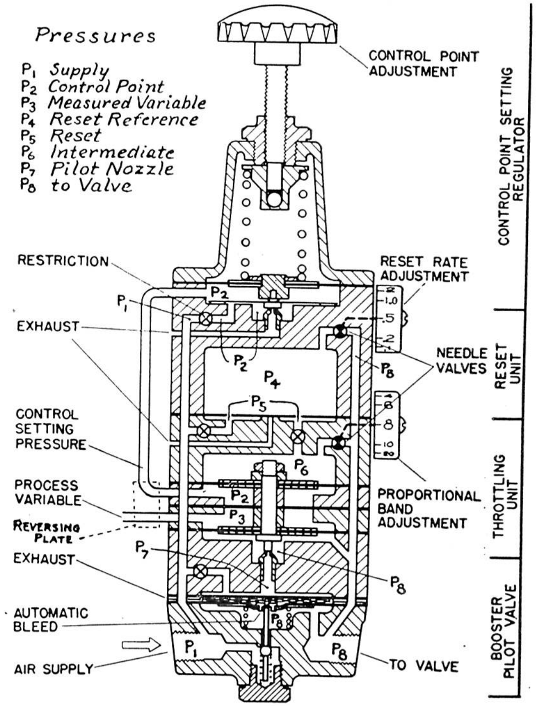


Fig. 9-17. Moore "Nullmatic Model 55" stack-type controller.

Fig. 9-18 shows a "Derivative Unit" for the "Nullmatic" system. It can be placed in the circuit ahead of the principal controller (one as shown in Fig. 9-17), or following it. With this derivative unit interposed, the result is to narrow the proportional band width as a function of the rate of change of the controller output, i.e. the rate of change of the process variable itself.

"Inverse Derivative."—Noteworthy feature of the Fig. 9-18 unit is the reversible section. When it is placed as shown, the unit generates the usual derivative action; when it is reversed, the unit *widens* the band-width as a function of the rate of change of the process variable. In other words, instead of temporarily narrowing the band-width when there is a process change, the unit temporarily widens the band-width; and instead of causing the output (to the valve) to lead the process, it causes this output to lag the process. For a detailed dissertation on this extraordinary mode of control, see the original disclosure* by C. B. Moore. In the six years since the introduction of "inverse derivative," practically all of the skepticism it met has vanished as its fields of usefulness have become recognized. The most widely recognized of these fields are: (1) liquid flow-rate control, (2) gas flow-rate control, (3) some pressure control applications, (4) some small-capacity liquid-level control applications, (5) some pH and oxidation-potential control applications.

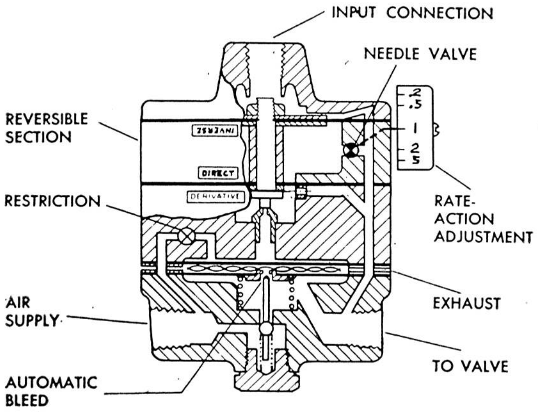


Fig. 9-18. Derivative unit for "Nullmatic" controller, providing both derivative and inverse-derivative actions.

NEGRETTI & ZAMBRA (BRITISH)

The Negretti & Zambra controller is designed to eliminate interaction between the control actions. The manner in which it does so will be seen from Figs. 9-19 and 9-20. Proportional and derivative and proportional and integral actions are generated and added. At the same time proportional action is subtracted. Experimental tests show that the interaction factor is in fact unity.

Eliminating interaction benefits the user in two ways: (1) the controller is easier to set up since actual *effective* action times are as set on the dials; (2) the phase advance obtainable if required is not limited by the effect of interaction. It will be remembered that the amount of derivative action (and hence of phase advance) which can be used depends on the form of the interaction factor.

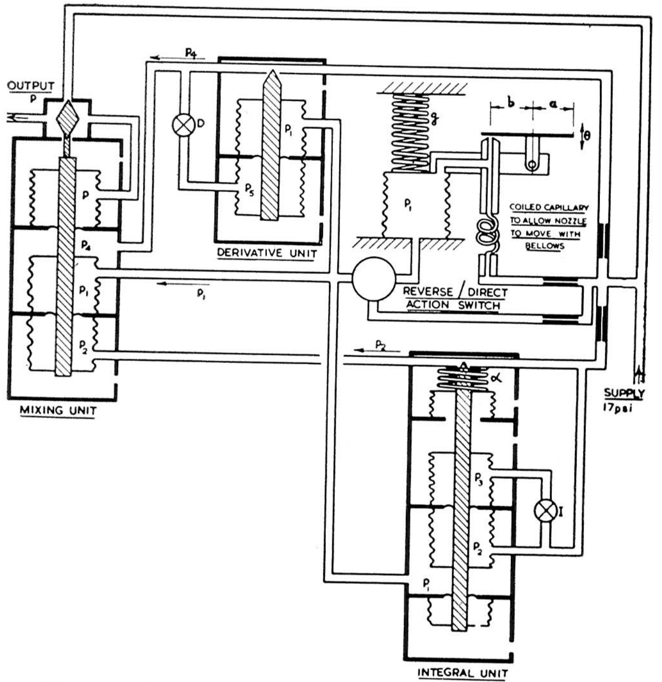


Fig. 9-19. Components of the Negretti & Zambra controller.

Experiment shows that the limitation on phase advance obtainable in practice is set by the impedance of the air valve in the mixing unit. For periods less than about 3 minutes, the phase advance obtainable falls below theoretical to about 50 degrees, depending on the capacity in the output. It should be noted that this is a high value and that by modifying the value concerned much higher values

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*C. B. Moore, "The Inverse Derivative—A New Mode of Automatic control," *Instruments*, Vol. 22, March 1949, pages 216-219.

can be obtained. At present it would be unusual, however, to require higher values for normal plant requirements—and if required for special application a low input capacity booster could be used to transmit output pressure to the regulating unit. Phase advance of 60° to 70° could then be obtained.

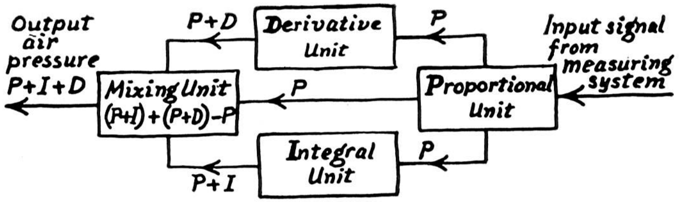

Fig. 9-20. Block diagram of Negretti & Zambra controller, showing separate derivative and integral units.

A feature of the Negretti & Zambra controller is the "plug-in" construction of subassemblies such as the compact integral and derivative units. The controller is at present made for use with mercury-in-steel thermal systems or other measuring elements giving a pressure or mechanical output.

REPUBLIC FLOW METERS CO.

The Republic Regulator is a force-balance controller operated by either pneumatic or hydraulic pressure. This description is based on pneumatic operation, but the principle is the same for hydraulic operation.

As shown in Fig. 9-21, pressure from some process vessel or line is applied to a measuring diaphragm. When the force thus created overcomes the force of the setting weight (or setting spring), the weighbeam moves on its pivot, tending to shut off the air bleeding from the nozzle and building up a back pressure under the amplifier diaphragm. The amplifier *starts* to move upward. In doing so, it pushes the weighbeam away from the nozzle, reducing the back pressure under the diaphragm. Pressure builds up under the amplifier diaphragm just enough to balance the downward force of the measuring diaphragm. The weighbeam will be held at just the distance from the nozzle necessary to produce a balance of all the forces involved.

(The motion of the weighbeam required to produce full pressure change in the amplifier is less than 0.004 in. so

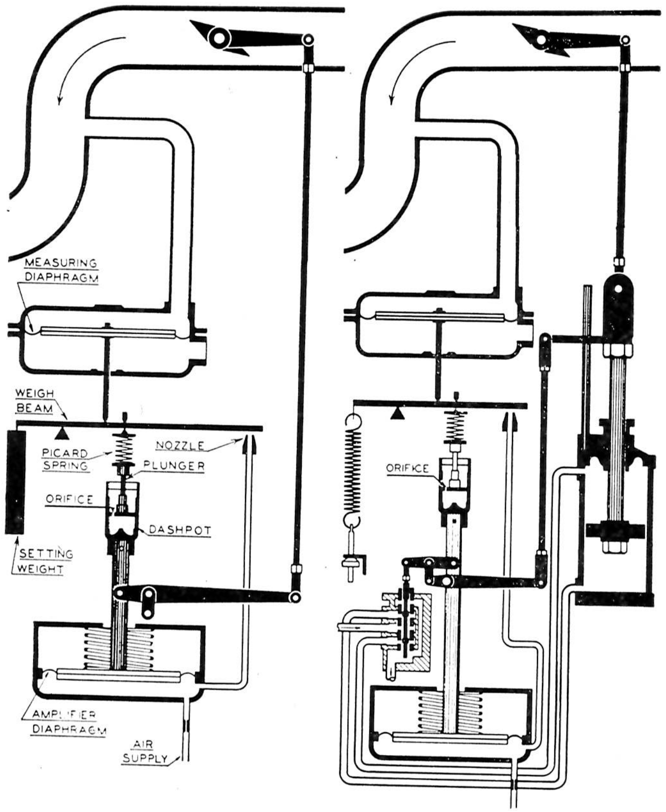

Fig. 9-21. The Republic regulator. Left, system for proportional plus integral control action; right, controller plus power cylinder.

that, from a practical standpoint, the measuring diaphragm need not move to produce full regulator action.)

Control Actions.—The link between the amplifier and the weighbeam can be either a spring, a dashpot, or both (as in Fig. 9-21). When only a spring is used, the force-balance principle produces only *proportional-position* control action. When only a dashpot (piston in oil-filled cylinder) is used, *proportional-speed floating* action is obtained because the piston moves at a rate proportional to the deviation from balance. Speed of piston movement is varied by changing the by-pass orifice.

When both the proportional spring and the dashpot are used, as in Fig. 9-21, the control action is *proportional plus integral*—that is, upon deviation of the variable, the amplifier immediately moves an amount proportional to the deviation and then moves at a rate proportional to the deviation.

Additional Amplification.—When power required to operate valves and dampers is more than the amplifier can supply, a pilot valve and power cylinder are added to the controller, as shown on the right in Fig. 9-21.

TAYLOR INSTRUMENT COMPANIES

1. *"Fulscope" Controller*

This instrument is interesting on account of the different mechanical arrangements used for changing its characteristics and the method employed for combining the integral and derivative actions.

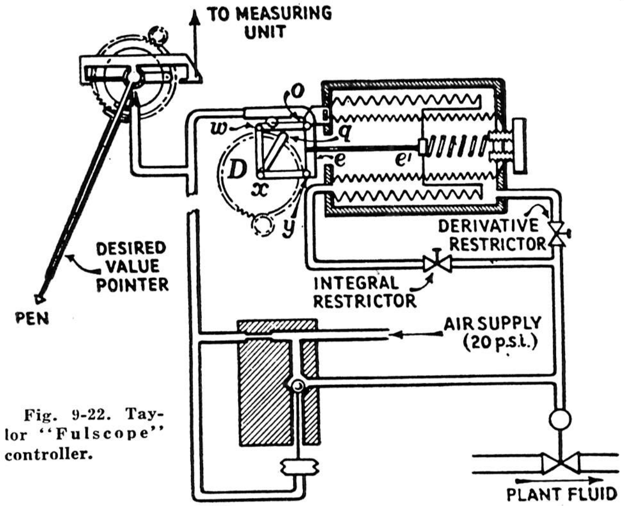

Fig. 9-22. Taylor "Fulscope" controller.

In most instruments examined so far, the integral and derivative restrictors have been placed in "series"; in the Fulscope they are in "parallel." This leads to different characteristics, as will be seen below.

The "flapper" consists of a cylinder carried on a lever. This lever is pivoted on a disk, which can be rotated to alter flapper/nozzle separation, and hence to adjust the desired value. The end of the lever is moved by the measuring unit. It will be noticed that the measuring unit can move the pen freely past the position at which the cylindrical "flapper" rests on the nozzle.

The sensitivity reduction required in a wide-band controller is obtained by a normal bellows feedback unit with a characteristic linkage for varying proportional band width, Fig. 9-22. (c). In the designs previously discussed, the "feedback" was arranged to decrease the flapper movement due to a given pen-arm movement, by means of a differential linkage. In this design, the nozzle is moved directly by the feedback system, as shown in the figure.

The proportional band is varied by adjusting disk D, which adjusts the effect of the feedback bellows. As q is moved towards y (Fig. 9-22), the feedback increases and the band widens. The normal range of adjustment is from 0.25 to 250 percent.

The "parallel" arrangement of derivative and integral action leads to an interaction factor of $(s + r)/(s - r)$, which is the easiest form to remember, or $[1 + (2r)/(s - r)]$, which is the more convenient. For many conditions a setting of $r/s = 1/4$ will give satisfactory results: the interaction factor at this setting will be 1.67 and the derivative action will give a phase advance of about 40°, when nominal integral action time is set to 1/1.67 of operating period.

2. *"Tri-Act" Controller*

The "Tri-Act" control circuit, Fig. 9-23, consists of two stages with three pneumatic loops connected in series and contained in one compact unit. The first stage embodies an adjustable proportional band with derivative action; the second stage employs a fixed proportional band and "automatic-reset" type of integral action. By providing derivative action in the first stage of the instrument, ahead of integral, this controller gives automatic start-up without overpeaking—advantageous on batch processes and on continuous processes that have occasional shut-down.

In the first stage of the controller, the transmitted process pressure and the desired-value ("set-point") pressure oppose each other. When these are equal, the pen and the desired-value pointer are together.

If a load change occurs in the process to increase the transmitted pressure to the controller, then this action unbalances the stack in the first stage and moves it down. As this happens, the baffle approaches the nozzle and its back pressure, which is the output of the derivative-action loop, increases. The derivative valve (marked "Pre-Act") offers a restriction to the flow of air to the "Pre-Act" chamber and delays the balancing action in the first stage. As a result, the first stage output pressure is higher for the period of time it takes the chamber to fill to the balance pressure. This is the derivative-action time.

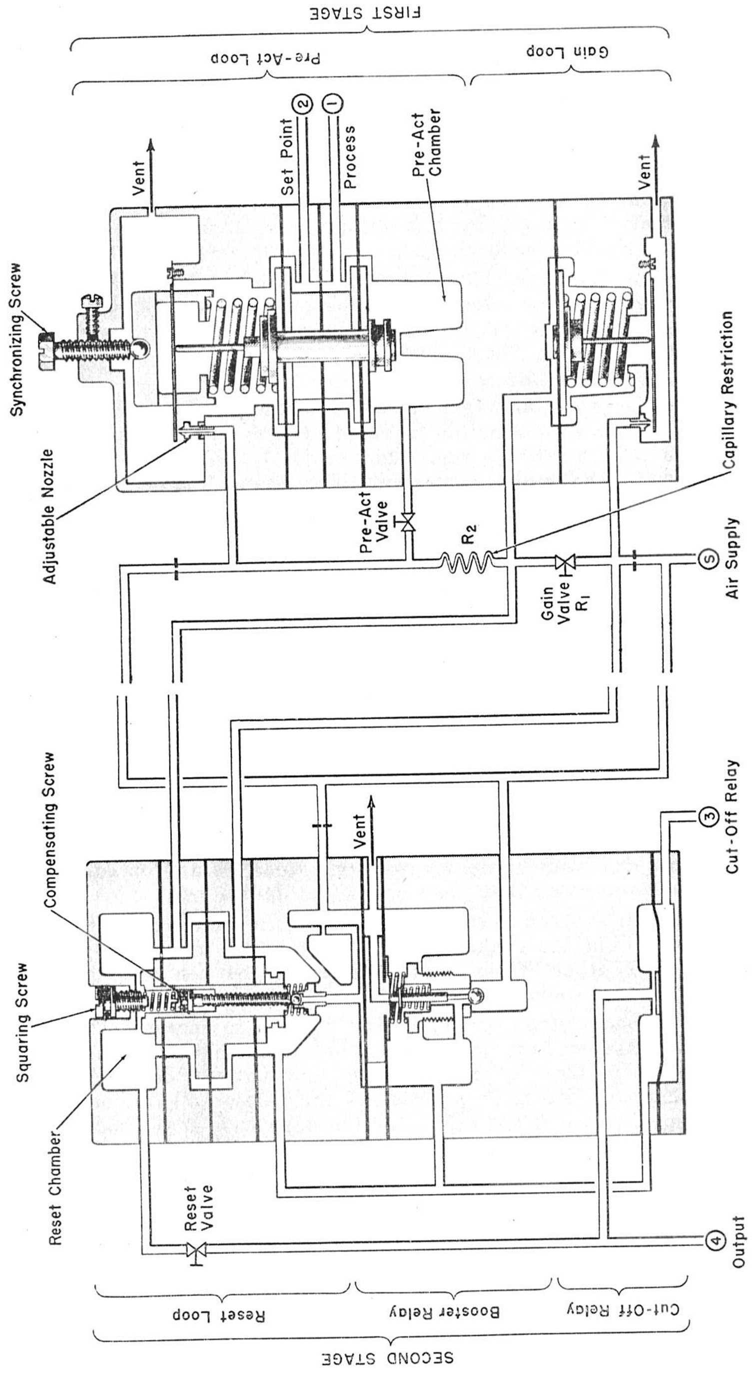

Fig. 9-23. Taylor "Tri-Act" controller. Although shown in two units, the controller is a single unit, as shown in Fig. 9-24.

The output of the derivative-action stage bleeds through the capillary restriction to the proportional-action stage (marked "Gain Loop"). This causes a pressure increase on top of the diaphragm and drives the baffle away from the nozzle. The nozzle back pressure decreases and is the output of the "gain loop." This output decreases the pressure on top of the diaphragm to its original value.

The "gain loop" output feeds the second stage of the controller where it is opposed by the balance pressure of the same loop. Because of a differential in these two pressures, the stack of the "reset loop" moves down. As this occurs, the ball approaches the nozzle and the nozzle back pressure increases to force down the "booster relay stack" (middle, left). As this happens, the booster relay output pressure increases. This is the output air pressure of the controller and also travels to the bottom of the "reset" stack to balance it. At the same time, this output pressure goes through the reset valve (upper left) to further reposition the stack and increase the output pressure of the controller. The rate at which the air goes through the valve to the reset chamber is the integral-action rate.

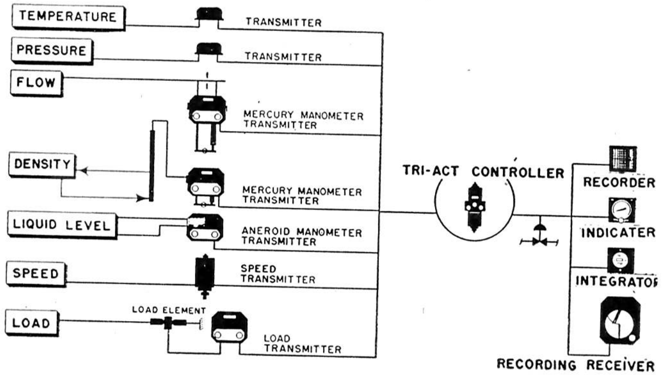

Fig. 9-24. Components of a typical modern control system, showing flexibility of applications. Transmitters and controllers can be mounted at optimum locations.

Fig. 9-24 shows the flexibility of the modern control system. The transmitters adapt the controller to any desired process variable. The controller can be mounted where lags are at a minimum. Miniature graphic-panel-type or conventional-size indicators and recorders can be mounted on the control board. Several manufacturers offer these flexible lines comprising pickup-transmitters, controllers, and panel indicator-recorders.

CHAPTER X

ELECTRONIC AND ELECTRICAL CONTROLLERS

Electronic and electric controllers are those which use electronic or electric techniques for generating the proportional, integral, and derivative actions. The input or output signals can be pneumatic simply by using an electric-to-pneumatic converter; most of the controllers have such converters as both input and output accessories.

In the chemical industries, some of the process variables to be controlled (temperature, conductivity, pH, etc.) are measured electrically and the outputs of the measuring systems can become, often without conversion, the inputs to the controllers. Other process variables (pressure, flowrate, etc.) are most often measured mechanically; and the displacement or deflection of a moving part is converted into an electrical change—a change of voltage, current, frequency, or phase—which becomes the input to the controller.

For safety reasons the power level of an electrical input to a controller in the chemical industries is extremely low, whence the necessity for high amplification in order to **operate valves, etc.**

EVERSHED & VIGNOLLES (BRITISH)

Electric Controller

This controller, Fig. 10-1, is based on a moving-coil-photoelectric system. It is designed to operate on an electric input signal varying from 0 to 30 ma. for full range of the measuring unit. Changes in the controlled condition are detected by orthodox detecting units and transmitted as a current in the 0-10-ma. range to the control unit and to any indicator or recorder required, by an electric transmitter based on a force-balance system.

Transmitter T gives an input current I_m which is proportional to the magnitude of the physical condition measured by detecting element DE. The input current is passed through one coil of a double-coil moving-coil instrument (enclosed in dotted rectangle in the figure). The moving coil system carries a shutter (s), so that deflection of the system causes more light from source L to fall on one or other of photocells P_1 and P_2.

The unbalanced current resulting from such a deflection is amplified by amplifier A and fed back to the second coil of the moving-coil system as current I_0, to restore the balance. Therefore I_0 is maintained proportional to I_m. It is also passed through regulating unit R.U. and a control action is obtained such that the output of the controller (i.e. I_0) will vary from 0 to 100 percent when the input from the detecting element varies over the full range, corresponding to 100 percent variation in I_m.

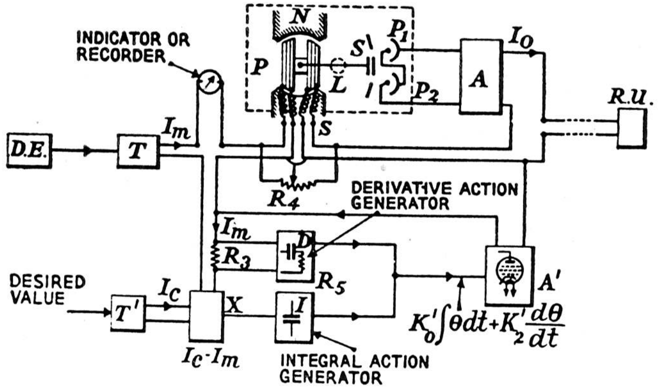

Fig. 10-1. Evershed & Vignolles "electric" controller. A vane, positioned by a moving-coil detector, changes light falling on two photocells. Photocell-output differential is error signal. Derivative action is generated by RC network in the input to the amplifier; integral action by the integral-action capacitor.

By placing a differential shunt R_4, as shown, across the two coils, the ratio $I_m:I_0$ can be varied. The proportional band width is therefore controlled by the setting of R_4; it can be varied from 2 to 600 percent.

Integral action is generated by:

(a) Obtaining a current proportional to deviation θ.

(b) Allowing this current to charge a large capacitor so that the potential of the capacitor at any time (t) after a deviation has occurred is $K'_0\int\theta dt$.

(c) Applying this potential to the grid of a pentode, which then gives a proportional current output $I_i = K_0\int\theta dt$;

(d) Feeding this current through the coil of the proportioning system which carries I_m.

The output of the controller will then be given by $I_o \propto I_m + I_i$ and so contains the integral action contribution.

The current proportional to θ, required by (a) above, is generated as follows. Transmitter T′, similar to T, gives a current I_C proportional to the desired value set. I_C is passed through one coil of a photoelectric system similar to that shown in the dotted rectangle, used to generate proportional action; I_m is passed through the other coil. This system is shown schematically by unit X in the diagram. The output of X is a current proportional to $I_m - I_C$, i.e. to θ.

The values of K'_0 (and K_o) are varied by changing the current in the bulb used to illuminate the photocells in the unit X. The resistor used to control the current is graduated in minutes (integral action time).

Derivative action is generated by allowing the potential difference across resistance R_3, which carries I_m, to charge a capacitance through resistance R_5. The potential across R_5 will therefore, as mentioned previously, be proportional to dI_m/dt or $K'_2\ (d\theta/dt)$.

This potential difference produced by derivative action unit D is added to that produced by integral action unit I and the total applied to the grid of pentode A′.

The current output of the pentode $(I_i + I_d)$ will thus be $K_o \int \theta.dt + K_2(d\theta/dt)$, and is fed with I_m through the proportional action unit as before.

The total ouptut of the controller (I_o) is now given by $I_o \propto K_1\ (I_m + K_0 \int \theta dt + K_2 d\theta/dt)$.

Derivative action time is adjusted by altering the value of R_5, which is a variable resistor calibrated in minutes (derivative action time).

It should be noted that there is no interaction between the integral and derivative actions and therefore the settings on the dials are actual action times.

HARTMANN & BRAUN (GERMAN)

"Regelux" Controller

As shown in Fig. 10-2, input signal x from the measuring unit is fed to one coil of a moving-coil system which is balanced by feedback from the photocell amplifier system to its second coil. Resistance-capacitance system I in the feedback circuit produces an output proportional to the rate of change of signal from the amplifier. This is fed back negatively and so produces the integral action. The integral action time is adjusted on resistor R_I.

The output from this stage is fed to the second stage, in which derivative action is added by the resistance capacitance system D. Derivative action time is adjusted on resistor R_D.

The electrical output of the controller, containing the proportional, integral, and derivative action contributions, positions a coil in the field of the permanent magnet (N S N) and so positions flapper F relative to nozzle N. The *final* output is therefore pneumatic.

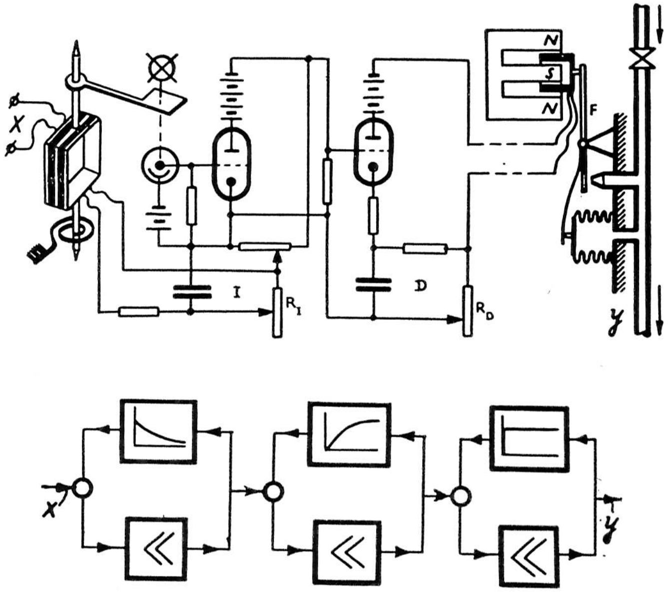

Fig. 10-2. Hartmann & Braun "Regelux" controller. Photoelectric cell develops error signal. Derivative and integral actions are generated by RC networks in the cathode circuits of the two direct-coupled amplifier stages. Bottom illustration shows functional actions.

The circuit arrangement is such that there will be interaction. The interaction factor is the same as that of the Bristol pneumatic controller described previously, namely $[1 + (r/s)]$. The most powerful derivative action will therefore be obtained when $r = s$ and the interaction factor will then be 2.

LEEDS & NORTHRUP

"Series 50" Electric Controller

This controller is essentially two potentiometer-type automatic null-balance units in parallel. The components of the complete system are shown in Fig. 10-3; the right-hand units of Fig. 10-3 are shown in greater detail in Fig. 10-4.

The "control slidewire" in the standard Leeds & Northrup potentiometer recorder (shown at the left in Figs. 10-3 and 10-4) follows movements of the "measuring slidewire." Any unbalance in this unit produces voltage e_1.

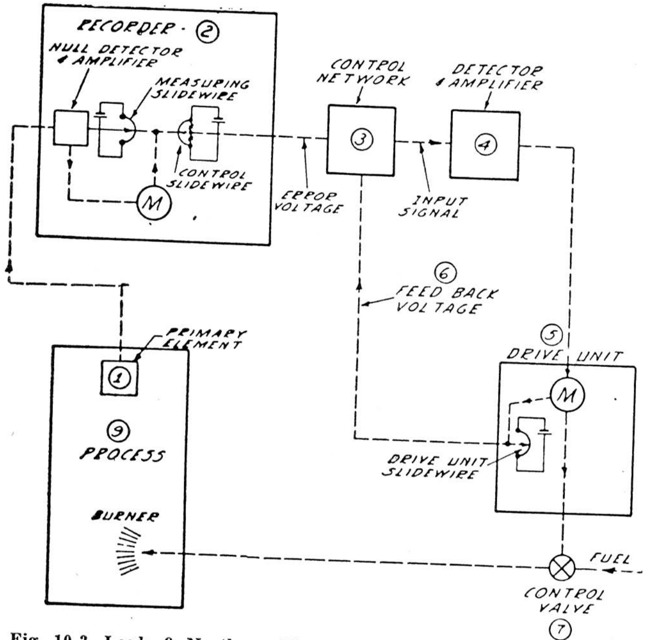

Fig. 10-3. Leeds & Northrup "Series 50" electric controller.

The second potentiometer unit positions the "valve slidewire" whenever voltage e_2 differs from e_1. The voltage e_2 is developed across the resistor shown in series with the valve-slidewire contact. (This resistor is R_1, but is not so labeled in the figure.) The "drive unit" motor positions the valve slidewire so that $e_2 - e_1$ is reduced to zero. Proportional action is thus obtained.

To obtain *integral* (*reset*) *action*, capacitor C_1 is added in series with R_1 and the valve-slidewire contact, as shown in Fig. 10-4. The drive unit will still maintain $e_1 = e_2$, but a potential e_3 will exist across C_1. If the current in R_I at any time is I, then $I\ R_I = e_2$, and the rate as which e_3 is changing is proportional to I. But $(e_2 + e_3)$ is the total output from the slidewire bridge, so that if $(e_1 - e_2)$ is maintained at zero, the valve slidewire contact must move continuously (to produce the additional voltage e_3) at a rate proportional to I, i.e. to e_1. By definition, integral action results.

To obtain *derivative* (*rate*) *action*, the network $R_2 - C_2$ is added as shown in Fig. 10-4. This network attenuates

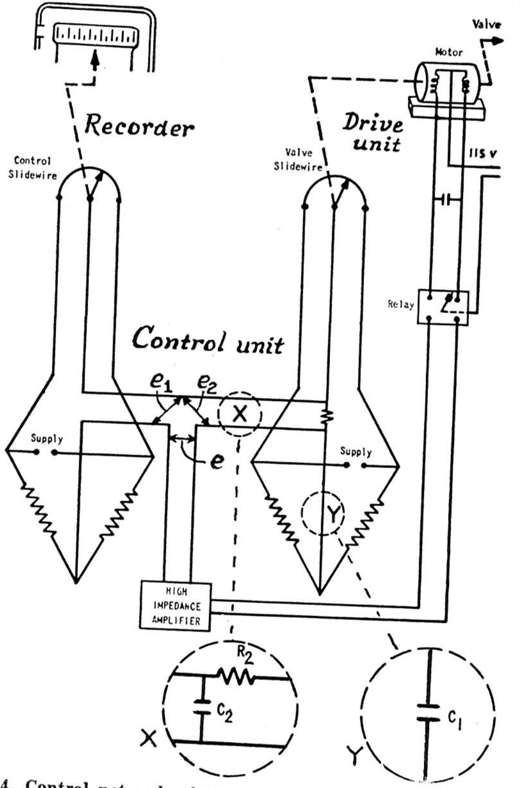

Fig 10-4. Control network of L&N controller operates on error signal representing difference between outputs of recorder potentiometer and drive-unit potentiometer. Resistor R1 is the unmarked resistor in series with the valve-slidewire contact, across which e2 is developed. X is derivative-action network. Y is integral-action network.

the rebalancing voltage (e_2) in proportion to the frequency of the voltage. The faster the signal, the greater the attenuation of the rebalancing signal, and the greater the signal to the drive unit. This, by definition, is derivative action. Control action times are set by adjustment of R_1 and R_2.

This method of generating the integral and derivative actions gives interaction between them. The interaction factor can be shown to be $[1 + \alpha\ (r/s)]$, where $\propto = [(C_1 + C_2)/C]$, where C_1 and C_2 are the integral and derivative action capacities and C is a constant for the controller.

MANNING, MAXWELL & MOORE

"American" Electronic Controller

This system comprises primary and final elements of customary sizes, and miniature units (recorder, indicator, controller, and manual positioner) for panel mounting. The components are shown in Fig. 10-5.

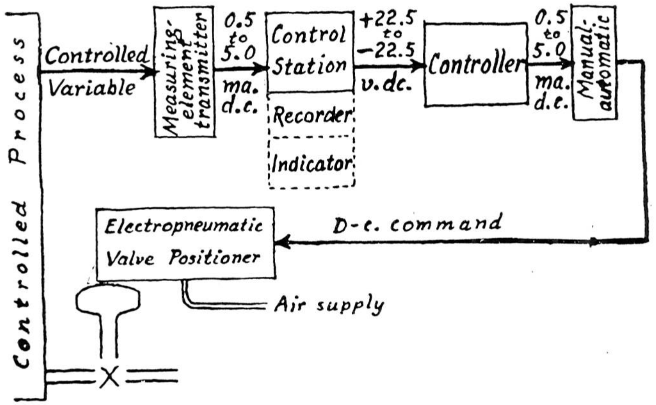

Fig. 10-5. "American" electronic process control system.

A distinctive feature is use of d-c. signal throughout, making the system insensitive to induced a-c. pickup and easily incorporated into auxiliary computer circuits if desired.

Fig. 10-6 shows the electromechanical "Set Point Section" of the control station, which selects the operating point, operates as a preamplifier, and delivers the signal to the controller. The input to the set point section is 0.5 to 5.0 d-c. milliamperes, at 70 ohms internal resistance (the output of all transmitters used with the controller); the output is plus 22½ to minus 22½ volts maximum, d.c. The set-point unit uses the maker's "Microsen" force-balance unit, comprising differential electro-magnetic coil, balance beam, and oscillator coil. Motion of beam detunes oscillator, causing feedback signal from amplifier to coil to restore balance of beam and oscillator frequency. Amplifier output goes to controller.

The "Type 163" controller is shown in Fig. 10-7. The input is plus 22½ to minus 22½ volts d.c. from the control station; the output is 0.5 to 5.0 ma. d.c. to the valve positioner via the manual-automatic station. Each triangular block represents a high-gain vacuum-tube amplifier.

Derivative (rate) action is obtained by delaying the degenerative feedback signal to the first amplifier. As the S1-C1 network is frequency sensitive, fast signals produce less negative feedback, resulting in higher amplifier gain. When derivative action is not desired, the input can be connected directly to the input to the second amplifier. Rate action is adjustable in steps between 0.01 to 1 minute, or 0.1 to 10 minutes.

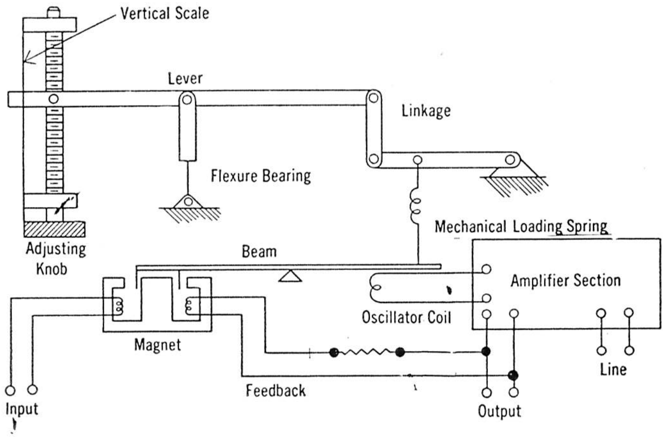

Fig 10-6. Set point section of "American" system. "Microsen" force-balance unit develops error signal, which is delivered to controller after preamplification.

Proportional action is obtained by varying the negative-feedback signal to the second amplifier through capacitor C21. The output current to the valve positioner develops a proportional signal across resistor P22. A portion of this proportional signal is fed back degeneratively to the second amplifier through C21, reducing its gain. Hence P22 controls the gain of the proportional-band amplifier. The band is adjustable from 1 to 200 percent.

Integral (reset) action results when resistor S21 is inserted in the circuit. This resistor refers the operating potential of the second amplifier to a fixed reference point. If the operating point drifts away from the control point, owing to load change, a steady input signal appears which operates through the full high gain of the second amplifier to restore the variable to the control point. For more rapid signals the gain of the second amplifier is reduced owing

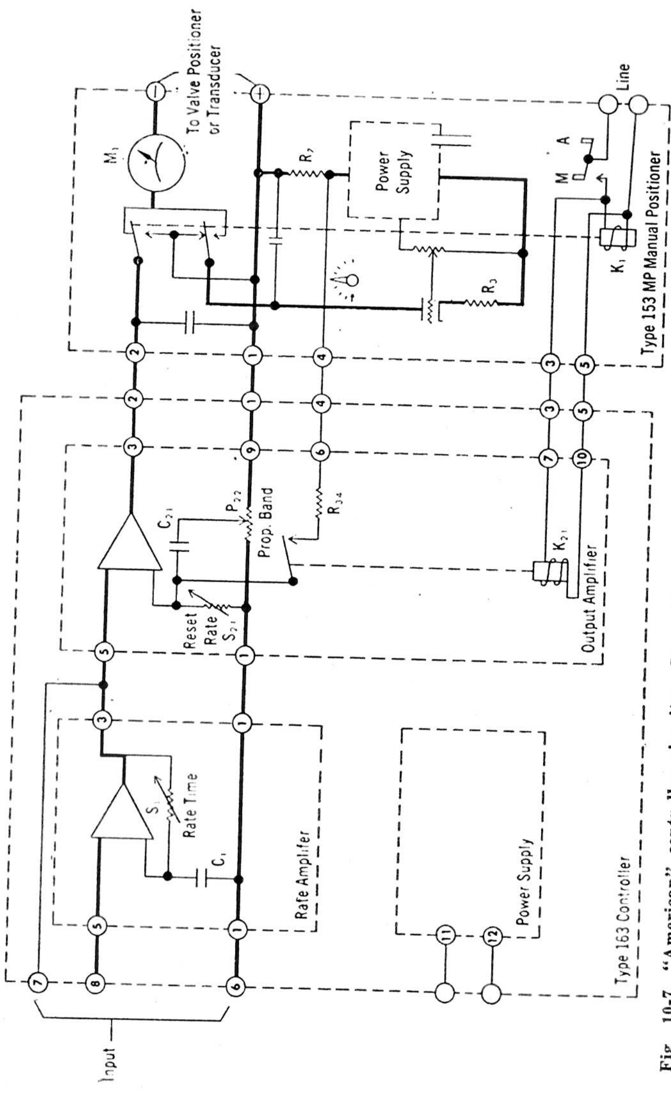

Fig 10-7. "American" controller circuitry. Derivative RC network is in negative-feedback circuit to first amplifier. Integral RC network is in second-amplifier stage. Manual positioner causes controller to follow manual setting, making "bumpless" transfer possible.

to the feedback signal through C21. Reset rate is adjustable from 1 to 100, or 0.1 to 10 repeats per minute.

Fig. 10-7 also shows the way in which the controller and manual positioner are interconnected to effect "bumpless" changeover from manual to automatic operation. This is done by having the controller output automatically follow the output of the manual positioner—the signal developed across R7 in the manual positioner is connected through R34 to reset capacitor C21 so that the controller output always follows the positioner output.

Primary-measuring instruments and control station have damped response and natural frequencies in excess of 4 cps. The controller break frequency is also approximately 4 cps.; that of output transducers is 1 cps. when operating into a volume of 65 cubic inches.

SCHOPPE & FAESER (GERMAN)

The circuit and schematic diagrams in Fig. 10-8 show the arrangement of this three-action all-electric controller. The cost of the controller will clearly depend on the cost of the magslips* (M) available to the makers.

The magslips are used as a-c. inductive potentiometers which give single-phase outputs of magnitude depending on the angular positions of the rotors.

Magslip M_1 accepts the input signal from the measuring unit and delivers a proportional output to the mixing transformer. The proportional band width is set on resistor R_p.

M_1 also feeds the motors m_1 and m_2 which, in turn, position magslips M_2 and M_3 through gear units G. The outputs of magslips M_2 and M_3 are fed into the mixing transformer to give integral and derivative actions respectively. It will be noticed that the systems m_1GM_2 and m_2GM_3 are similar systems, both of which will produce an output proportional to $\int\theta dt$. The output of magslip M_3 is, however, fed into the mixing transformer in the opposite sense to that of M_2 (and M_1). Hence the effect of the m_2GM_3 combination is to generate derivative action, whereas m_1GM_2 generates integral action.

The action times are set on the resistors R_I and R_D: proportional band width is set on R_p.

The mixing-transformer output is amplified to drive servomotor m_3, which positions the regulating unit. As shown in Fig. 10-8, the positional feedback is supplied by the magslip M_4 to the mixing transformer.

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*The term "magslip" is used to denote angular position transmitting systems known by various proprietary names such as "Selsyn," "Autosyn," etc.

The design is such that no interaction (in the usual sense) occurs. Effective action times and proportional band will therefore be as read on the dials and it would be expected that high values of phase advance can be obtained.

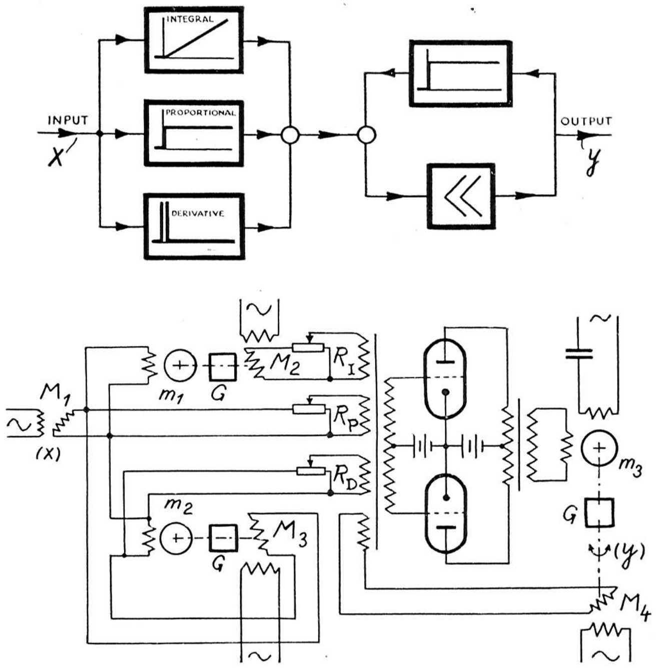

Fig. 10-8. Schoppe & Faeser controller uses angular-position transmitters (magslips) and a mixing transformer to add the control actions.

The Swartwout Co.

"Autronic" Electronic Controller

This system comprises primary and final elements of customary sizes, but only miniature units for mounting on panels: the controller here described, the recorder, the indicator and the manual-control station (Fig. 10-9).

One distinctive feature of the controller is the conversion of the controlled variable into a proportional 60-cps. alternating voltage between 0 and 0.5 volt. All of this maker's measuring elements are designed to furnish an alternating voltage in this 0-to-0.5 volt range and hence are interchangeable. For flow, pressure, etc., conversion is effected by inductive pickups; for temperature, the transmitter comprises a platinum-resistance primary element and an adapter unit containing bridge components to provide the 0-0.5-volt alternating voltage.

Another feature of the controller is that its output is a direct current varying from 4 to 8 ma.

Electronically, the controller consists of four sections in cascade: proportional amplifier, phase-sensitive amplifier, derivative-action amplifier, and integral-action amplifier.

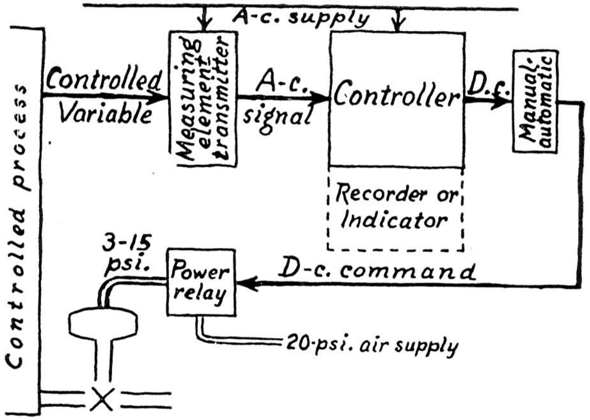

Fig. 10-9. Swartwout "Autronic" electronic control system.

Proportional amplifier (A in Fig. 10-10): The signal voltage input (from the primary-element transmitter) and the desired-value voltage input are both connected to the a-c. amplifier. The difference between these two input voltages—the error signal—is amplified. The proportional bandwidth setting controls the gain of the a-c. amplifier, whose output is proportional to the error signal. The over-all amplification of the proportional amplifier is varied by feedback through the adjustable proportional-band network, calibrated from 3 to 200 percent band-width. The proportional amplifier is a 3-stage a-c. amplifier with resistance-capacitance coupling, and self-bias on the second two amplifier stages, as shown at A.

The phase-sensitive rectifier (between A and B) converts the a-c. output of the proportional amplifier into a d-c. voltage which is proportional to the error signal and of correct polarity. The controller is changed from reverse to direct action by reversing the phase of the reference voltage to the phase-sensitive rectifier.

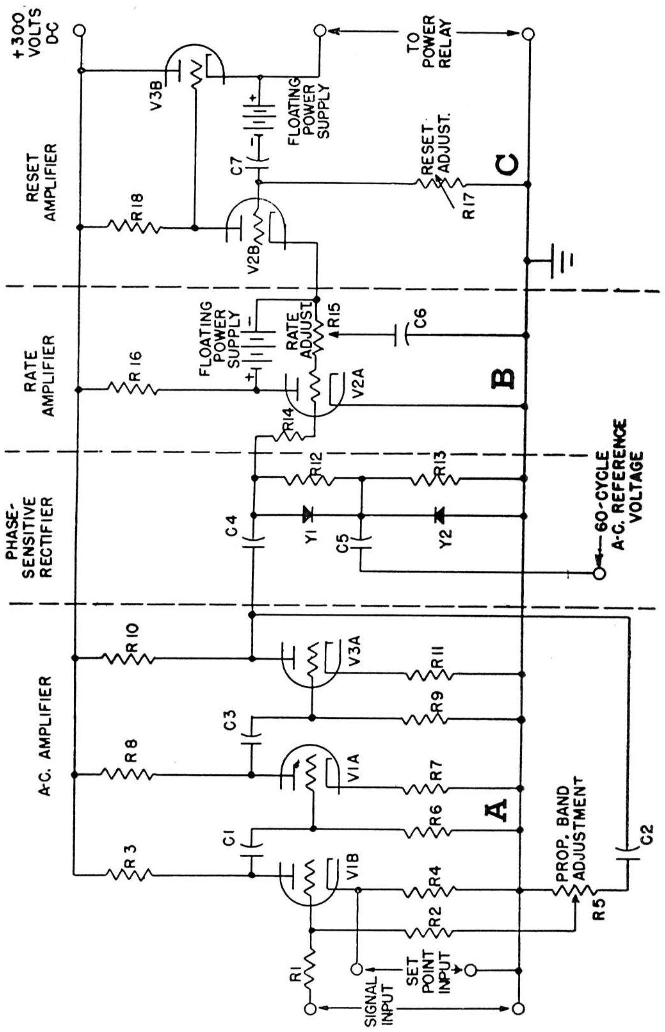

Fig. 10-10. Controller circuitry of "Autronic" controller. Separate derivative and integral action amplifier stages are used.

The derivative-action amplifier (B) has a network that causes the d-c. amplifier to have an output that varies in proportion to both the magnitude and the rate of change of the signal input.

When no derivative action is used with the controller, this amplifier has a voltage gain of one, obtained by feedback. When derivative action is used, feedback is through the derivative network, which delays the feedback. For sudden changes in voltage input, there is no feedback to reduce the normally high gain of this amplifier. Capacitor C_6, in combination with R_{15} interposes a delay in the feedback of triode V_{2A}: sudden input changes give greater output changes because capacitor C_6 shunts high-frequency components and reduces the negative feedback to the grid. Derivative time is adjustable from 0.05 to 8 minutes.

The integral-action amplifier (C) has an amplification of greater than 200 for steady-state or slowly-changing values of input. On more rapidly changing inputs, however, the integral network provides a transient voltage feedback which reduces the amplification. This provides the entire controller with an initially wide proportional bandwidth on sudden changes, which slowly reduces itself to a narrow band. The rate of integral action is adjustable from 0.03 to 20 repeats per minute.

CHAPTER XI

ELECTROPNEUMATIC AND MECHANICAL CONTROLLERS

Elliott Brothers (London) Ltd.

"Trimode" Controller

This controller can be adapted to receive either electric or pneumatic signals; in the form shown in Fig. 11-1 it is used with an electric input. The output in either instance is an air pressure of the standard range.

Referring to Fig. 11-1, it will be seen that the proportional band is adjusted electrically and the electrical output from the proportional unit is fed to an electropneumatic converter. The output from this converter is added to integral and derivative action units as shown in Fig. 11-2. Both actions are generated in a silicone-filled system and applied to a balance arm as shown. The restrictors are of needle valve type. This controller has been designed with the basic theory well in mind and contains refinements shown only partly in the three figures.

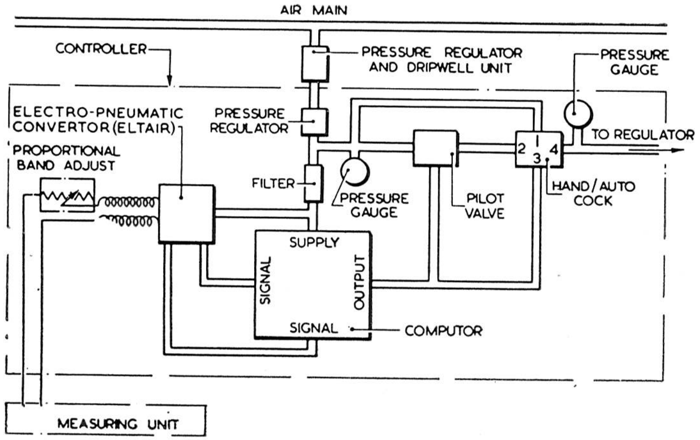

Fig. 11-1. Components of the "Trimode" controller.

The theoretical equation expressing the behavior of the controller shows that the interaction factor is $1+(5/4)(r/s)$. This is only of interest to the user, however, as a means of finding the ratio r/s which gives maximum phase advance—for those applications in which it is required. The ratio, which is not critical, is found to be $r/s = 0.8$. The interaction factor is then 2, and the phase advance available is about 45° for $S =$ operating period.

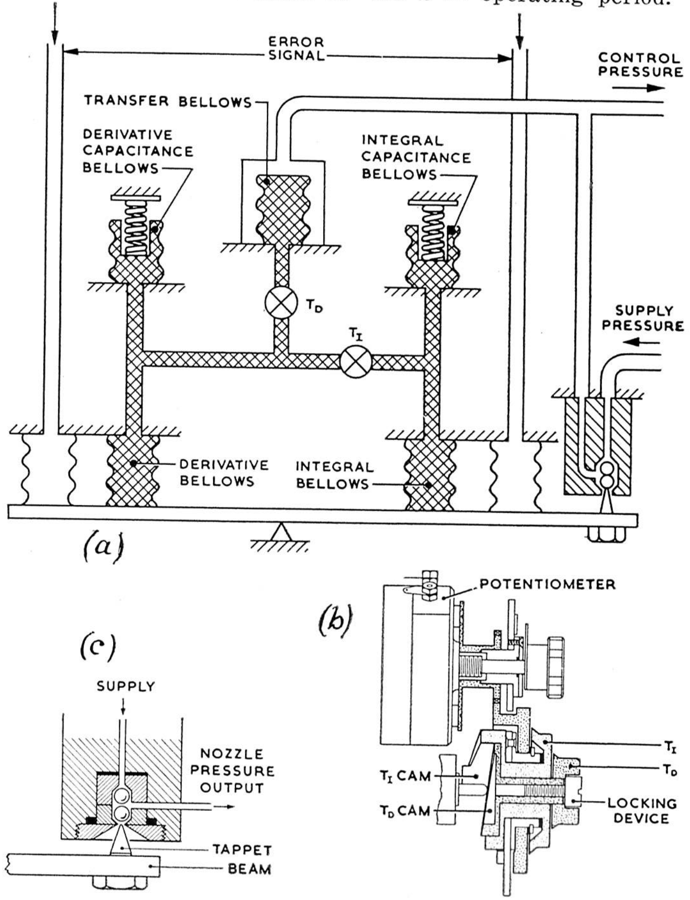

Fig. 11-2. Force-balance unit of the "Trimode" controller. Top illustration shows force-balance unit that controls relay at right-hand end of beam. Relay is shown at lower left. Lower right shows inter-relation between dials so that constant proportional band width is maintained irrespective of independent adjustment of R and S, the derivative and integral action times.

It is important to note that the user in this instance is not concerned with the nominal times (r and s) but with the effective times (R and S) which will be set on the dials. For $r/s = 0.8$, $R/S = 0.2$; this is the value of R/S recommended by the makers.

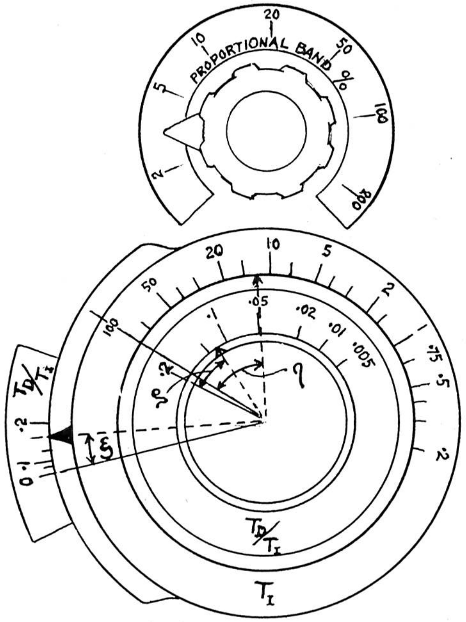

Fig. 11-3. Dial arrangement of "Trimode" controller, consisting of a proportional band dial, a dial with pointer for integral action time, and a derivative action knob which is set against required value of R/S on the scale carried by the integral action dial. A lock on the dials insures that the effective value of the proportional band width remains constant, independent of the values of integral and derivative action times.

This controller is especially interesting in that provision has been made for setting the *effective* proportional band width, and the integral and derivation action times, directly on the setting dials.

The setting dials appear as in Fig. 11-3. They consist of a proportional band dial, two dials and a knob. The inner carries a pointer, which is set against the desired integral action time, on the scale engraved on the outer dial. Derivative action time is set by means of the knob by setting its

pointer against the required value of the ratio R/S on the scale. Dials can be locked in this position, so that R/S remains constant irrespective of the values of R and S.

The pointer carried on the left-hand side of the outer dial must be set at the value of R/S required on the short scale. This ensures automatic adjustment of proportional band width, so that its *effective* value remains constant.

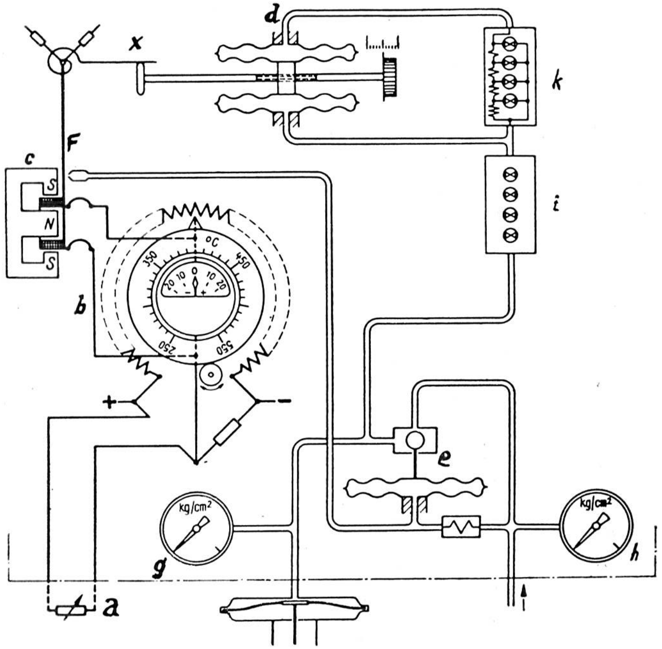

Fig. 11-4. Siemens & Halske "Electro-Pneumatische" controller, which uses pneumatic technique for control actions, but positions the flapper electrically.

Siemens & Halske (German)

"Electro-Pneumetische Regler"

This controller (Fig. 11-4) generates its actions pneumatically in a manner similar to other controllers with integral (h) and derivative (i) units arranged in "series." The interaction factor is thus $1 + (2r/s)$, and the most powerful derivative action will be available with $s = 2r$. At this setting the interaction factor will be 2.

Interesting features of the controller are that it uses an operating air pressure much lower than normal and that it has an electric system for providing motion of the flapper (F) proportional to deviation. The controller is designed for a resistance thermometer (a), as the detecting element and the unbalance from the resistance bridge (b) is fed to the coil shown in the field of a permanent magnet (SNS). Any out-of-balance current produced by a deviation from desired temperature will thus cause a proportional movement of the flapper. Desired value is set on the bridge and proportional band width by adjusting the point X (on the lever controlling the restoring spring of flapper F by the movement of the feedback bellows d.

The temperature at which control is holding the process is read by adding the reading (+ or −) of the center pointer (which gives deviation from desired value) to the desired value set on the circular scale as shown. The low air pressure used necessitates the unusually large diameter of the capsule which operates the relay valve from nozzle pressure.

MECHANICAL CONTROLLERS

It is in the field of ratio control—of great importance chemically—that there are to be found control systems whose purely mechanical components are undoubtedly the principal components and whose pneumatic or electrical components play subordinate roles. The reason is that the determination of ratios by levers, gears, cams, etc., is of unquestionable accuracy. There is no "error" or "drift" in a gear-train; and the backlash, if present, is ordinarily negligible.

Proportioneers, Inc.

"*Synchro-Master*"

This automatic control system utilizes the differential principle of control. Perhaps the simplest example of this principle is an equal-arm horizontal Class I lever (fulcrum in center) which automatically balances two vertically-directed forces A and B, force A being unpredictably variable, force B being exerted by a solenoid, and the automatic control feature consisting of a carbon rheostat actuated by the lever. Whenever the value of A changes, the lever starts to tilt, causing the rheostat to increase or decrease the solenoid's force in order to rebalance A and B and bring the lever back to horizontal. The ratio in this example is 1:1.

In order to utilize this principle in controlling rotating machines, a geared mechanical differential is substituted for the lever. Fig. 11-5 shows a machine A against which the rotation of machine B is to be synchronized. The rotation of A drives side gear 1 counterclockwise while the rotation of B drives side gear 2 clockwise. If gears 1 and 2 are turning at exactly the same speed, differential pinion 3 will revolve, but its spider-shaft 4 will not move. Any difference in the speeds of gears 1 and 2 will cause spider-shaft 4 to be carried in the direction of the faster-moving side gear. By linking spider-shaft 4 to a means of controlling the power flow to machine B, an increase in the speed of A will increase the power flow to B until B's speed again matches A's. An increase in the speed of B will cause its power to be reduced until its speed again matches the speed of A. Therefore, B's speed must follow A's at any load within B's power range.

The control rate of a differential used in this way is asymptotic in character since, as the speeds of the side gear approach synchronism, the *rate* of control change decreases. This is an inherent anti-hunting characteristic and, since the side gears run continuously, the forces which position the spider-shaft 4 are the same whether it is moving or not.

In chemical process control, most ratios are other than 1:1. Referring again to the simple lever, ratios other than 1:1 can be produced by relocating the fulcrum so that the relative lengths of the two arms are inversely proportional to the required ratio between the two forces. The differential in Fig. 11-5 can be made to do the same thing by changing the drive ratios to the side gears. If the number of teeth on the pinion of machine A is reduced one-half it will have to turn twice as fast to bring its side gear up to the speed of that driven by machine B. Any fixed ratio is possible by proper gearing and if a speed changer or integrator is connected between the machine and its pinion, variable ratios are obtained. Fig. 11-6 is a refinement of this scheme arranged to provide a variable speed output with positive rotation through zero to reverse. The variable speed drive to side gear A can be adjusted to turn A either faster,

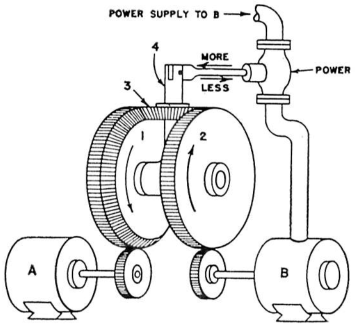

Fig. 11-5. "Synchro-Master" controller principle. Any difference is speed between motors causes differential spider to vary power to follower motor.

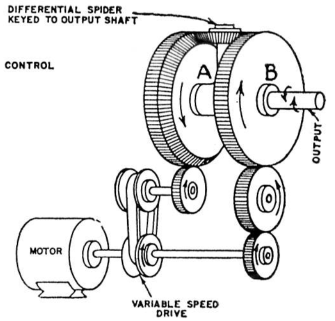

Fig. 11-6. Arrangement for variable-speed control with "Synchro-master" technique.

slower, or the same sped as B. Therefore, the differential spider and the output shaft will turn forward, reverse or stand still and carry full torque at all speeds including zero.

Constant flow-rate.—By using a synchronous electric motor and a speed changer to drive the leading side of the differential, a precision governor is obtained. The following side is driven by the machine to be governed and the differential control lever is linked to its speed control. This provides an isochronous governor which will hold the machine at set speed regardless of changes in load. A governor of this type may be applied to anything which rotates and which is subject to infinitely-variable control. For example, it can become a constant rate flow controller for liquids by driving the following side from the spindle of a positive-displacement meter in the liquid line. The differential control lever is attached to a flow control valve in the meter line.

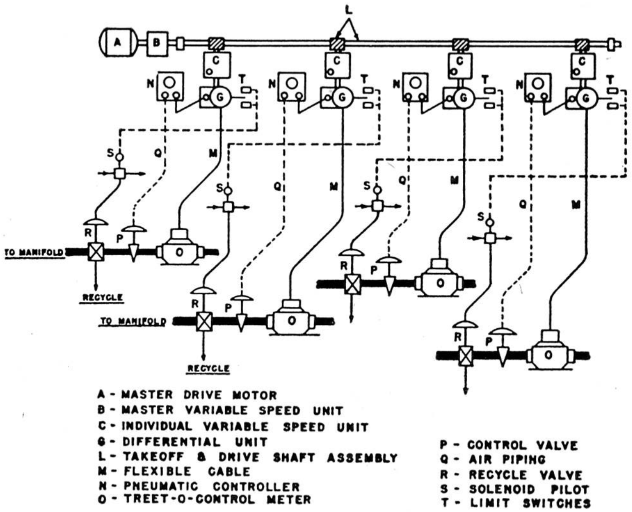

Fig. 11-7. Automatic continuous volumetric blender controlling flow rates of four products in exact ratio.

Proportional Control.—Now, by combining the constant flow control with the leading element system, an arrangement capable of simultaneously controlling the flow-rates of several liquids is obtained. Fig. 11-7 is a schematic layout of Proportioneers, Inc. "Automatic Continuous Volumetric Blender" which utilizes this system. Synchronous motor A driving through integrator B (speed changer) to line shaft L is used as a master speed reference. By adjusting the setting of integrator B, the speed of master lineshaft L can be changed, which produces a simultaneous and equal change in the input speed to each of the secondary integrators C. To illustrate the control of one component, assume that the master integrator B is set to turn the leading line shaft at 100 rpm. and that the secondary integrator C has been set to drive the leading side of synchronizer G at 10 rpm. The following side is driven through flexible cable M connected to the spindle of meter O. If meter O is geared to pass one gallon per spindle revolution it will have to rotate at 10 gpm. to balance the differential in synchronizer G and hold it in a neutral position. Should the meter pass more or less than exactly 10 gpm. the differential will move from its neutral position and unbalance the sensitive element in the air controller N which will reposition control valve P until the 10 gpm. rate is restored. By adjusting the secondary integrator C, the controlled rate of flow through the meter and valve may be set for any value relative to the rotation of the master line shaft. Therefore, the ratio of the various components is established in terms of percent by calibrated dials on each of the secondary integrators and the over-all rate of total blend is fixed by the master integrator which drives line shaft L. Over-all errors in actual installations are said to average less than 0.5 percent, independent of changes in head, temperature and viscosity.

CHAPTER XII

SETTING UP A CONTROLLER ON THE PLANT

In Chapter IV, theoretical considerations with regard to the control characteristics of plant and controllers were discussed with the object of giving a basic understanding of the fundamental principles involved in matching controller characteristics to plant characteristics. An instrument was also described, which can be used to obtain plant data from which can be drawn a diagram to show the frequency response of the plant.

It was shown how this diagram can be used to find the control characteristics of the plant and facilitate matching the controller to them to give optimum control quality.

It was not anticipated that this technique would be used generally for setting up, or selecting, controllers. The necessary analyzers are not available to most plants and it has in any event been found that, in most applications, actual analysis of the plant is not necessary for this purpose. (It is, however, desirable that as many plant analyses as possible should be carried out, in order to build up knowledge of plant characteristics for further work in this field.)

It was hoped that the discussion would stimulate interest in a fundamental approach to the whole problem and at the same time supply the mental tools for tackling specific difficulties. Experience has shown that a knowledge of the general theory and an appreciation of the factors determining plant characteristics make the setting up (and selection) of controllers a much more rapid process and moreover a much easier matter for those without a long experience of process control. With a good working knowledge of the plant and a sound grasp of the significance of the two kinds of lags and their dependence on their distribution in the plant, it should be possible to set up a controller quickly and successfully in most applications normally encountered.

This does not mean that the use of the analyzer is confined to the infrequent very difficult problem. It may be remembered that, in the first chapter, the importance was emphasized of designing plants specifically for automatic control. It was also stated that the present knowledge of plant characteristics was not sufficient to supply the plant design engineer with adequate data for this purpose.

The function of the analyzer is to assist in obtaining these data with all possible speed. Some progress has already been made, but it will be some time before a clear picture of any but the general requirements can be presented to the designer of a particular plant.

Meanwhile, the plant chemist or engineer will probably find the following suggestions useful for setting up controllers on the plant. They should be interpreted and applied in the light of the theoretical background which has been supplied.

CONSIDERATION OF PLANT CONTROL REQUIREMENTS

The first matter to consider is the requirements which the control system is expected to meet. In most practical instances some degree of compromise must be made, so that the desired quality of control can be achieved economically. In general, one of the following will be required:

(a) minimum deviation following a disturbance;
(b) minimum time interval before return to desired value, after a disturbance;
or (c) minimum offset due to changes in operating conditions.

The difficulty of providing these requirements will of course depend not only on the plant but on the nature of the disturbances anticipated. The relative importance of (a), (b) and (c) will depend on the nature of the process and the products. For example, a process which is strongly exothermic may commence to "run away," with serious consequences, if the temperature is allowed to rise only a few degrees momentarily. In another process, occasional rapid fluctuations in temperature may not be important while a small sustained temperature change may completely ruin the product. In this case a quick return to desired value is essential and offset must be eliminated as far as possible.

In some applications proportional action alone will be adequate, because the proportional band width can be made sufficiently narrow to make offset negligible and the proportional control factor (μ) will be sufficiently great to maintain small deviations with quick return to desired value. In general, however, it is necessary to employ derivative action in addition if (a) and (b) are critical requirements.

If with proportional action alone, or with derivative action, the band width is wide enough to permit considerable offset—and when (c) is of primary importance—then integral action must be employed. It must be repeated, however, that integral action is disadvantageous to the control system in all other respects and it should therefore only be used when it is really necessary.

CONSIDERATION OF THE PLANT CHARACTERISTICS

The two important matters are the anticipated changes in operating conditions and the lags in the control loop.

If supply and demand changes are expected to be small and disturbances slow, proportional action alone may suffice, and integral action will be almost certainly unnecessary. Rapid, transitory changes will call for derivative action.

The lags in the control loop must be estimated and their number, relative magnitudes and distribution (with respect to the detecting element) must be assessed. It is also necessary to know whether the lags are of the transmission or distance-velocity type.

Distance-velocity lags must if possible be reduced; derivative action cannot be used to counteract their effect on control. Often a straightforward rearrangement of plant, or detecting element, can be made to reduce these lags, especially when the plant is being designed.

Most plants possess predominantly transfer lags. These are most troublesome, for a given "total lag," when they are all of the same order of magnitude; the most favorable situation occurs when one lag is very much larger than all the others. A number of quite small lags can have a very bad effect on control quality.

On an existing plant the only lags which it may be possible to reduce are those associated with the measuring system itself and with the transmission of signals to and from the controller. Detecting-element transfer lag is generally most serious in temperature measurement and it should be reduced by any means possible. Lag in pneumatic transmission can be reduced, where long lines make this necessary, by using transmitters or boosters. Systems employing large diaphragm-operated regulating units, especially when these are at the end of long air lines, will repay attention in this respect.

It is important to remember that lags increase in importance as they occur nearer the detecting element.

If the unavoidable lags remain considerable, and especially if they are all of the same order and numerous, the proportional band width must be wide. Derivative or integral action, or both, will be necessary, depending on the requirements and anticipated operation conditions.

SUGGESTIONS FOR SETTING UP THE CONTROLLER

The considerations outlined in the previous chapters may lead to a fairly clear indication of the controller characteristics needed in a given application, but in many instances the following procedure will be found useful.

It is assumed that a three-action controller is available and that it has been checked and adjusted according to the maker's instructions. If it is found necessary to use only proportional action, or proportional plus either integral or derivative alone, a simpler controller can be substituted later if any economy can thus be made.

(1) Find the optimum proportional band width for proportional action alone. Commence with a wide band and narrow it until continuous hunting is obtained. Then widen the band until a subsidence ratio of about 3 is obtained.

(2) Read the proportional band width (say x percent). This determines the maximum amount of offset which can occur, i.e., $(x/2)$ percent of full scale range. If this offset is too great, decide whether addition of derivative action can be expected to reduce the band width sufficiently. If the band width requires a decrease of about 1/3, derivative action should be tried.

(3) If the proportional-action test shows that deviations of the controlled condition due to plant disturbances are too great, or if the period is too long, derivative action must certainly be added.

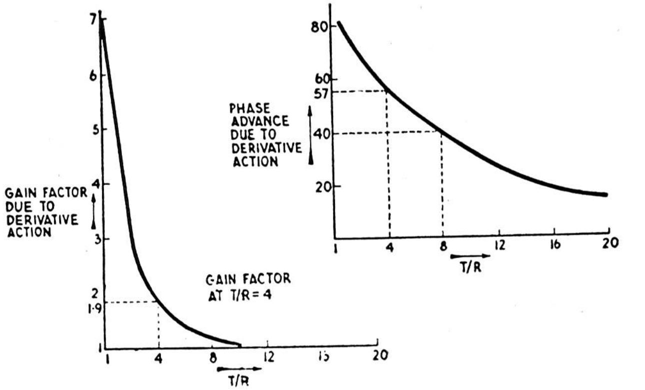

Fig. 12-1. Gain factor (left) and phase advance (right) due to derivative action.

It may be permissible to emphasize once more that the purpose of derivative action is to introduce phase advance into the controller and so allow the control loop to operate at a shorter period. At the same time, it allows the use of a narrower band width.

As has been seen previously, there is a limit to the amount of phase advance which can be utilized in this way, because of the increasing gain introduced by derivative action as the action time is increased relative to the plant period.

In Fig. 12-1, it can be seen that the phase advance at $T/R = 10$ is appreciable, while the additional gain is negligible.

Hence the next step is to set $R = T/10$. The period will be shorter with derivative action and it can be estimated fairly safely as being about 4/5 of the natural period. Therefore observe the natural period T_N and set $R = (1/10)\ [(4/5)\ T_N]$.

(4) With this setting for R, narrow the proportional band to find the new band width which gives a subsidence ratio of 3.

(5) If the reduction in band width is still insufficient, the period still too long, or the control of disturbances inadequate, the value of R can be increased. The shape of the curves in Fig. 12-1, however, show that the extra gain introduced becomes increasingly large. In practice, values of T/R greater than 4 are rarely found to bring any advantage.

(6) It should be noted that the operating period will continue to be reduced by decreasing T/R (and so increasing phase gain). Hence, if period is the chief criterion, T/R can be made considerably higher with advantage than if narrow proportional band width and control of deviations are the first requirements.

7) If offset is still too large, i.e., if μ is too small, integral action must be used.

When used without derivative action, the optimum setting is normally $S =$ plant period (T_1). T_1 must, of course, be estimated before S can be set equal to T_1. As a guide, T_1 will be longer than T_N by a factor of 1.1 to 1.3 in many applications.

Adjust the proportional band to give the 3:1 subsidence ratio. Although the band width may have increased by 50 percent, offset will be eliminated. In other respects, control will of course be worse owing to the decrease in value of μ.

(8) If, as a result of using proportional plus integral action alone, deviations and period are too great, derivative action must then be used as well.

(9) It is not possible to give *general* quantitative suggestions for setting up a three-action controller, because each has a different interaction factor. This implies also a different optimum ratio for derivative to integral action time. Several makers approach the problem by linking the action settings so that this optimum ratio is achieved. Unless this is done, it is only possible to approach the problem logically by obtaining the necessary information from the maker. It is not given in all makers' instruction manuals.

A safe rule, however, is that integral action time must be equal to or less than the *operating* period; otherwise it will have too little effect to be useful. At the same time, as much derivative should be added as is required to reduce overshoot and period to satisfactory values. The general aim is always to reduce the proportional band width as much as possible, bearing in mind the influence of the interaction factor; i.e., proportional band width setting divided by interaction factor equals effective proportional band width.

It must be remembered that if derivative action is added to a controller already matched to the plant with proportional plus integral action only, then the effective integral action time will be increased above the nominal value set on the dial. The factor by which the integral action time is increased by the addition of derivative action will be equal to the interaction factor.

In such circumstances, therefore, the integral action time setting should be decreased, so that the effective time remains equal to or less than the operating period when the derivative action is added.

The above suggestions apply to continuous processes which run at a constant desired value. Batch process control requires separate treatment, which cannot be given here. It may, however, be useful to point out that, if integral control is employed on a thermal batch process, overshoot is bound to occur when the batch is initially brought up to temperature.

Unfortunately, the amount of offset which can be tolerated without damage to the product is often so small that integral action must be employed, and at the same time little or no overshoot can be allowed. In such circumstances, it is strongly advised that the instrument maker should be given full data on the problem and asked for advice to obtain the operation of his control equipment in the particular application.

CONCLUSION

It is hoped that the information contained in this serial will assist in spreading a knowledge of the principles upon which the application of process control is based, and that this general treatment of the subject will be found useful in the study of particular control problems and installations.

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