Optimum Settings for Automatic Controllers

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In this paper, the three principle control effects found in present controllers are examined and practical names and units of measurement are proposed for each effect. Corresponding units are proposed for a classification of industrial processes in terms of the two principal characteristics affecting their controllability. Formulas are given which enable the controller settings to be determined from the experimental or calculated values of the lag and unit reaction rate of the process to be controlled. These units form the basis of a quick method for adjusting a controller on the job. The effect of varying each controller setting is shown in a series of chart records. It is believed that the conceptions of control presented in this paper will be of assistance in the adjustment of existing controller applications and in the design of new installations.

A PURELY mathematical approach to the study of automatic control is certainly the most desirable course from a standpoint of accuracy and brevity. Unfortunately, however, the mathematics of control involves such a bewildering assortment of exponential and trigonometric functions that the average engineer cannot afford the time necessary to plow through them to a solution of his current problem.

It is the purpose of this paper to examine the action of the three principal control effects found in present-day instruments, assign practical values to each effect, see what adjustment of each does to the final control, and give a method for arriving quickly at the optimum settings of each control effect. The paper will thus first endeavor to answer the question: "How can the proper controller adjustments be quickly determined on any control application?" After that a new method will be presented which makes possible a reasonably accurate answer, to the question: "How can the setting of a controller be determined before it is installed on an existing application?"

Except for a single illustrative example, no attempt will be made to present laboratory and field data, to develop mathematical relations, or to make acknowledgment of material from published literature. A paper covering the mathematical derivations would be quite lengthy as would also a paper covering laboratory and field-test results. Work on these phases of the subject is still under way, and it is expected that the results will be published at a later time when convenient. It is believed advisable to publish the present paper without delay in order to make the information available for use by the many persons interested in the application of automatic-control instruments. To these persons the present subject matter is of much greater interest than the other phrases of the study which are being omitted.

To simplify terminology we will take the most common type of control circuit in which a controller interprets the movement of its recording pen into a need for corrective action, and, by varying its output air pressure, repositions a diaphragm-operated valve. The controller may be measuring temperature, pressure, level, or any other variable, but we will completely divorce the measurement portion of the control circuit and speak only of the pen movement in inches; 1 in. of pen movement might represent 1 or 1000 deg F, or a flow of 1 or 1000 gpm. The actual graduation will be of no moment in a study of control.

Our controller will translate pen behavior into behavior of a valve; the relation between the two behavior patterns is determined by the setting of each control effect. The term valve covers any similar device, i.e., a damper or rheostat which must be operated by the controller in order to maintain correct process conditions.

PROPORTIONAL RESPONSE

In spite of the multitude of air, liquid, and electrically operated controllers on the market, all are similar in that they incorporate one, two, or, at most three quite simple control effects. These three can be called "proportional," "automatic reset," and "pre-act."

Proportional Response. By far the most common effect is “proportional response," found in practically all controllers. It gives a valve movement proportional to the pen movement, that is, a 2-degree pen movement gives twice as much valve movement as a 1-degree pen movement. Simple spring-loaded pressure-reducing valves are really proportional-response controllers in that, over a short range of pressure, the valve is moved proportionally from one extreme to the other.

Sensitivity. The measure of proportional response is called “sensitivity" or "throttling range;" the former being valve movement per pen movement, the latter its reciprocal or the pen movement necessary to give full valve movement. Either sensitivity or throttling range describes the magnitude of proportional response, though in this paper each response will be measured in units which increase as the relative valve action per pen action increases. In the case of proportional response, the unit will accordingly be called "sensitivity."

Proportional-response sensitivity in some controllers is not adjustable; in most, however, it may be adjusted either continuously or in steps over a considerable range. If we define sensitivity as the output pressure change per inch of pen travel, it is apparent that the limits would be from zero (manual control) to infinitely high (on-off control). Perhaps the widest range of adjustment is found in one controller with sensitivity continuously variable from 1000 to 1 psi per in. A sensitivity of 1000 gives 1 psi output change for each 0.001 in. of pen travel.

Sensitivity adjustment is necessary if optimum control stability is to be attained. It is common knowledge that control with infinitely high proportional response is always unstable, oscillating continuously. True, on certain applications the oscillation may be of such small magnitude that it is not objectionable and, if the surges in supply are not serious in their effect on other portions of the process the control obtained may be entirely acceptable.

Industry generally demands control of the "throttling" type rather than "on-off" since, a proportional-response controller, set in any sensitivity below some maximum, will produce a damped oscillation and eventually straight-line control.

Amplitude Ratio. Sensitivity adjustment affects primarily the stability of control. On any application there is a definite and

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easily determined point called the "ultimate sensitivity" (S_u), above which any oscillation will increase to some maximum amplitude, and below which an oscillation of any size will diminish to straight-line control. Stability may be measured in terms of "amplitude ratio," the relative amplitude of any wave to that of the wave which preceded it. A controller set at the ultimate sensitivity gives an oscillation with an amplitude ratio of 1; above the ultimate sensitivity, an amplitude ratio greater than 1; and below the ultimate, an amplitude ratio less than 1.

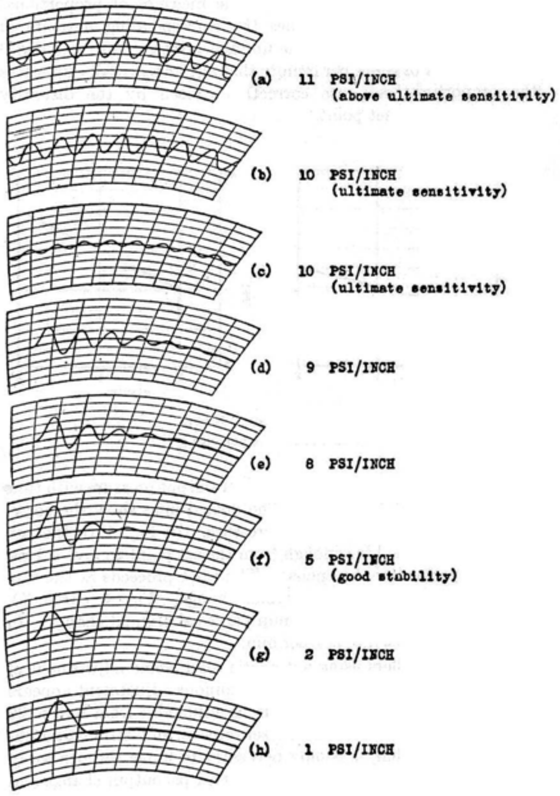

FIG. 1 AMPLITUDE RATIO VERSUS SENSITIVITY
(Effect of disturbance)

Amplitude Ratio Versus Sensitivity. Fig. 1 shows the effect of sensitivity adjustment on a typical application. The oscillation was started by a momentary change in valve position. Curves (b) and (c) were produced at the ultimate sensitivity, which in this case was 10 psi per in. Curve (a) was produced at a sensitivity of 11 psi per in. (110 per cent of S_u). Curves (d) to (h) show the successively smaller amplitude ratios produced as the sensitivity was lowered to 90, 80, 50, 20, and 10 per-cent of the ultimate (9, 8, 5, 2, and I psi per in.).

In Fig. 1 and succeeding charts, each division is 0.1 in. and each time interval represents 0.625 min.

Regardless of the ultimate sensitivity of any control application, the relationship between amplitude ratio and sensitivity, given as percent of ultimate sensitivity, remains about as shown in Fig. 2. The ultimate sensitivity thus appears to be a good common point for consideration of sensitivity adjustment on most control applications.

Offset and Load Change. In considering the curves of Fig. 1, the most desirable setting from a stability standpoint would be (h), produced at quite it low sensitivity (10 per cent of ultimate). It should be noted in passing, however, that as sensitivity is reduced the period of oscillation increases slightly, which in itself is undesirable. The drawback of using sensitivity settings a great deal lower thin the ultimate value stems from the limitation of proportional response e.g., that only one valve position can be maintained when the pen is at the desired set point. A "load change," any disturbance in the process requiring a sustained alteration of valve position, will cause the pen to shift away from the set point far enough to give the required valve movement. The magnitude of this, shift or "offset" varies inversely with the sensitivity setting used and directly with the required change in

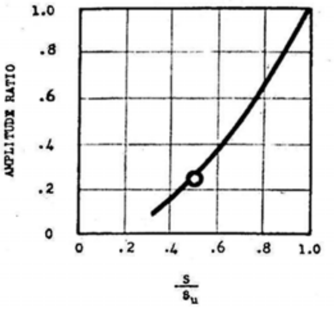

FIG. 2 AMPLITUDE RATIO VERSUS SENSITIVITY

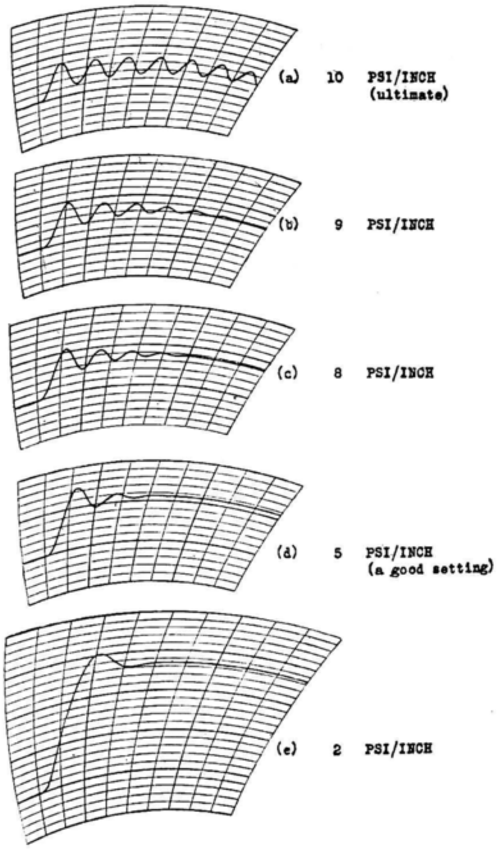

FIG. 3 OFFSET VERSUS SENSITIVITY
(Effect of load change)

valve position. Fig. 3, curves (a) to (e), illustrates this point. Curve (a) shows the offset caused by a load change requiring a 2.8 psi change in output pressure with sensitivity at 10 psi per in. Since this is the ultimate setting, an Amplitude ratio of 1 results and a lower setting is indicated. As the sensitivity is decreased to 9, 8, 5, and then 2 psi per in., the offset from this load change increases and the amplitude ratio decreases.

Amplitude Ratio Versus Offset. The rational adjustment of proportional-response sensitivity is then simply a matter of balancing the two evils of offset and amplitude ratio. For most applications a good compromise is, the sensitivity which gives an amplitude ratio of 25 per cent. This sensitivity will be very nearly one half that of the ultimate sensitivity, as shown in Fig. 2. An excellent and rapid method of sensitivity adjustment is to find the ultimate sensitivity and then simply cut it in half. Fig. 1, curve (f), shows that an amplitude ratio of 25 per cent is achieved by this setting on the application under test. Fig. 3, curve (d), shows the result of a load change requiring a 2.8 psi change in controller output pressure. The sensitivity setting of 5 psi per in. allows an offset of 2.8/5 or 0.56 in. with a 25 per cent amplitude ratio.

On many air-operated controllers, the sensitivity adjustment is calibrated either in terms of sensitivity or throttling range. On such instruments the trick of halving the sensitivity to obtain a good setting is quite simple; on those calibrated in throttling range the setting should be doubled, since this unit is the reciprocal of sensitivity. The sensitivity of older instruments with arbitrary adjustment scales may be easily found by moving the pen a definite distance. and noting the resulting output-pressure change. This test run at a few points will enable the user to plot a sensitivity-conversion scale.

The statement that a sensitivity setting of one half the ultimate with attendant 25 per cent amplitude ratio gives optimum control must be modified in some cases. At times a lower sensitivity is preferable. For example, the actual level maintained by a liquid-level controller might not be nearly as important as the effect of sudden valve movements on further portions of the process. In this case the sensitivity should be lowered to reduce the amplitude ratio even though the offset is increased by so doing. On the other hand, a pressure-control application giving oscillations with very short period could be set to give an 80 or 90 per cent amplitude ratio. Due to the short period, a disturbance would die out in a reasonable time, even though there were quite a few oscillations. The offset would be reduced somewhat though it should be kept in mind that it can never be reduced to less than one half of the amount given at our previously defined optimum sensitivity of one half the ultimate.

On processes involving wide changes in load, one condition is often encountered which must be considered here. A controller perfectly adjusted for one load condition may start oscillating under another load. If the ultimate sensitivity is checked at the new more difficult load, it will be found lower than at the original easy load condition. Consequently, the sensitivity must always be adjusted so that the correct stability is achieved under the most difficult load condition. Obviously the amplitude ratio will then be lower at the easy load.

AUTOMATIC-RESET RESPONSE

The second most common response found in modern controllers is "automatic reset," Its only purpose is to eliminate offset. In action it detects any disparity between pen and set point and gives a slow continuous valve movement in the proper direction to correct the offset. Furthermore, the rate of valve movement is proportional to the distance between pen and set point. Automatic reset then may be defined as a response giving valve velocity proportional to pen displacement from set point.

Some controllers give a constant valve velocity with the direction depending upon whether the pen is above or below the set point. This is a special case and will not be considered further. Neither will those controllers having automatic reset alone (floating response) be considered in this paper. It appears that the floating response controller is most useful on partially "self-controlling" processes.

Reset Rate. As sensitivity was the measure of proportional response, "reset rate" becomes the corresponding measure of automatic-reset response. The units of reset rate are minutes^{-1} or the number of times per minute that automatic reset duplicates the proportional-response correction caused by the disparity between pen and set point.

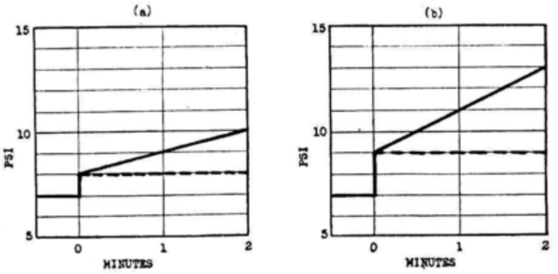

FIG. 4 RESET RATE
(Reset rate= 1 per min.)

Fig. 4(a) and (b) shows the course of output pressure with time for a reset rate of 1 per min. The dotted lines show the corresponding proportional response pressure. In Fig,. 4(a), the pen was moved and held far enough from the set point to give a 1 psi change in proportional response. The reset proceeds at the rate of 1 psi per min per 1 psi original change. Fig. 4, curve (b), shows a reset rate of 2 psi per min per 2 psi original change. In both cases the reset rate is 1 per min.

In most controllers using automatic reset, some adjustment of the reset rate is provided, though continuous adjustment appears in only a few. In one, the reset rate is adjustable from zero to 20 per min. In order to determine reset rates on an instrument without a calibrated dial, it is only necessary to move the pen away from the set pointer far enough to cause a 1 psi output change and note the additional output-pressure change per minute. The same value can be put on the reset adjustment in controllers other than those of the air-operated type, by making a sustained pen change from the set point, noting the altered valve position which results from proportional response and the additional travel at the end of 1 min from automatic reset. The reset rate is the travel from reset divided by the travel from proportional.

Optimum Reset Rate. Fig. 5(a) to (e) shows the effect of reset-rate adjustment on control. Fig. 5, curve (a), resulted from a load change equivalent to 2.8 psi output pressure with a reset rate of zero, in other words, only proportional response. This curve is the same as Fig. 2(d) except that the sensitivity is reduced from 50 per cent of ultimate to 45 per cent of ultimate. A reset rate of 0.5 per min gives the slow return toward the set point shown in Fig. 5(b). As the reset rate is increased to 1, to 1.5, and to 2, in Fig. *5(c), (d),* and (e), the return becomes more and more rapid. At the same time, instability and period of oscillation increase. In general, curve (d) of Fig. 5 would be considered the optimum in that it gives reasonably rapid return without excessive loss of stability or excessive increase in period.

Optimum Reset-Rate Adjustment. The actual reset rate which gives a recovery curve similar to Fig. 5(d) varies widely on different control applications. As will be pointed out later, the reset rate appears to vary inversely as the time lag of the application. At present, however, we are more interested in finding a simple method for determining the correct setting.

It has been found that the period of oscillation (P_u) produced at the ultimate sensitivity (Su) is a good index of required reset-rate adjustment. This period should be measured when the amplitude of oscillation is quite small, such as on curve (c) of Fig. 1, where the period is about 0.8 min. The optimum setting of reset rate, that which produces a recovery curve similar to Fig. 5(d), is usually about 1.2/Pu. On the process being tested, the reset rate of 1.2/0.8 or 1.5 was used for curve Fig. 5(d).

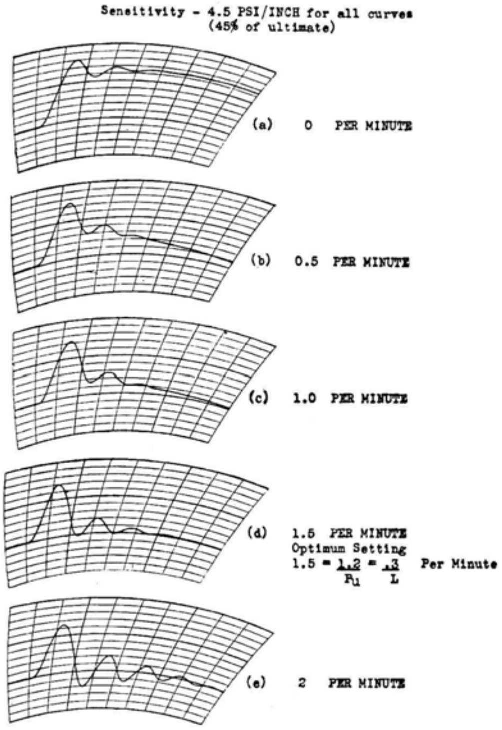

FIG. 5 RESET RATE VERSUS RECOVERY
(Load change)

In adjusting a controller with proportional and automatic-reset responses, the sensitivity which just gives a small sustained oscillation should be determined (S u), and the period of oscillation (Pu) in minutes noted. Optimum controller setting will then be approximately

$$\text{Sensitivity} = 0.45S_u$$
$$\text{Reset rate} = 1.2 / P_u$$

Note that the recommended sensitivity has been reduced from 0.5Su to 0.45Su, Were this not done, the addition of automatic reset would have increased markedly the amplitude ratio This tendency of automatic reset to decrease stability is one of its bad features; the other is its tendency to increase the period of oscillation.

While a reset rate of $1.2 / P_u$ is generally recommended, recovery curves with the same amplitude ratio may be obtained at a higher reset rate and lower sensitivity. In general. however, this procedure results in recovery curves with longer period and greater initial deviation, both of wlich are detrimental.

PRE-ACT RESPONSE

The latest control effect made its appearance under the trade name "Pre-Act." On some control applications, the addition of pre-act response made such a remarkable improvement that it appeared to be in embodiment of mythical "anticipatory" controllers. On other applications it appeared to be worse than useless. Only the difficulty of predicting the usefulness and adjustment of this response has kept it from being more widely used.

This pre-act effect is as distinct a response as proportional and automatic reset. Pre-act simply gives an additional valve movement proportional to the rate of pen movement. It is used only in conjunction with proportional response.

Pre-Act Time. Since pre-act response is an additional output pressure change per rate of pen movement, its unit is the "pre-act time" in minutes

(psi) per (psi per min) = min

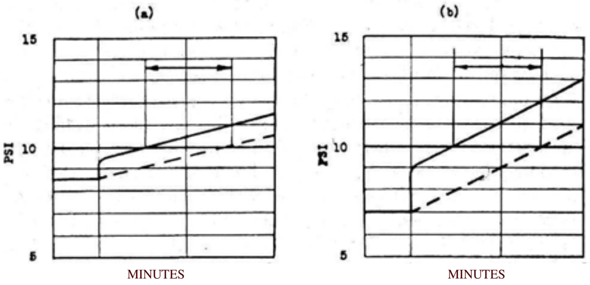

FIG. 6 PRE-ACT TIME
(Pre-act time = 1 min.)

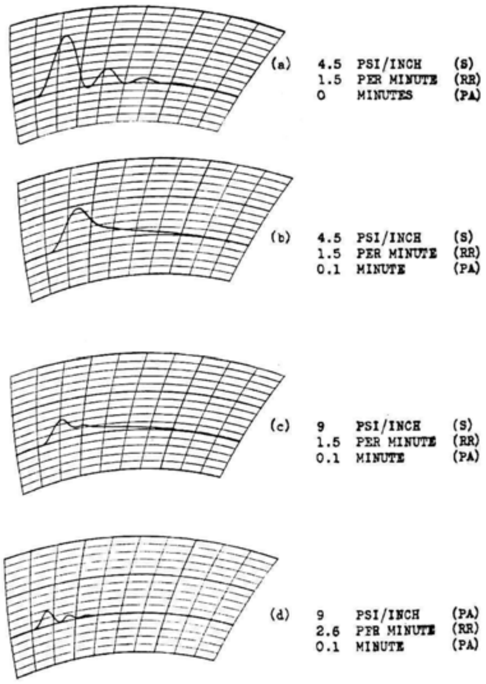

FIG. 7 CONTROL WITH PRE-ACT
(Load change)

To visualize this unit, assume a controller pen moving away from the set point at such a rate that a proportional-response output change of 1 psi per min results (dotted line of Fig, 6(d)). Addition of 1 min pre-act time will cause the controller output to follow the solid line 1 psi higher, i.e., the pre-act response 1 psi additional for 1 psi per min proportional-response change. Without altering the pre-act setting, a pen velocity twice as great would give 2 psi additional pressure as shown Fig.6(b). The time by. which the solid line of Fig. 6(a) and (b) leads the dotted line is the pre-act time, in this case 1 min.

Recently, several industrial instrument companies have made this control effect available in a more or less adjustable form. In one, the dial is calibrated in terms of pre-act time over a range of 0.2 to 10 min.

Use of Pre-Act Response. Pre-act response has been, successfully used on applications which give a period of oscillation greater than about 0.4 min. It is not generally useful on pressure- or flow-control applications and rarely on control-of liquid level. though this is not a hard and fast rule. To date, it been used most widely on temperature control applications.

The effect of pre-act on control is shown in Fig. 7. Fig. 7 curve (a) repeats curve (d) of Fig. 5, which represented, about the optimum control obtainable with proportional and reset responses only. Without altering these settings, the addition of 0.1 min pre-act time changes the recovery curve for the same 2.8 psi load change to that shown at (b). The increased stability is an indication that a higher sensitivity nay be used so it is accordingly, increased to 9 psi per in. The resulting curve (c) shows a much smaller initial deviation without excessive amplitude ratio, but an excessively, slow, return toward the set point, indicating that a faster reset rate is needed. (Compare with Fig. 5(b).) Increasing the reset rate to 2.6 per min. produced the curve Fig. 7(d) representing approximately optimum control using the three responses.

A comparison of curves, Fig. 7(a) and (d), discloses that the pre-act response has improved control in several respects. Maximum deviation from the set point has been cut 71 per cent, period of oscillation has been reduced 43 per cent, and the time required for the oscillation to die out his been halved.

Pre-act response does not replace automatic reset response since it ceases to act when the pen becomes stationary. However, while reset increases period of oscillation and decreases stability, the effect of pre-act is just the opposite,. On the debit side for pre-act lies only the increased difficulty of adjusting three responses instead of two, but the use of the basic unit, pre-act time, allows the setting to be determined from the period of oscillation.

Optimum Pre-Act Time Adjustment. It his been found that, for a wide range of control applications, the optimum pre-act time depends directly upon the, period of oscillation used to determine the adjustment of the reset rate. In fact the pre-act time should be about $^1/_8$ of the period of a small amplitude oscillation at the ultimate sensitivity.

To adjust a controller with proportiona1, automatic reset, and pre-act responses, determine the ultimate sensitivity (S_u) and note the period (P_u) of a small-amplitude oscillation at this sensitivity. The optimum settings will then be approximately

Sensitivity $= 0.6\ S_u$
Reset rate $= 2 / P_u$ per min
Pre-act time $= P_u / 8$ min

On some applications, the sensitivity with pre-act can be greater 0.6 S_u. This is illustrated by the test application, which allowed sensitivity of 0.9 S_u (Fig. 7(d)). We have found that the setting is generally between 0.6 S_u and 1 S_u. In many applications, a sensitivity of 0.6 S_u will be sufficiently near the optimum setting.

If, at these settings, the amplitude ratio is too high, each adjustment should be reduced slightly. When using the system of units proposed in this paper a decrease in the setting of any response increases stability. (Actually pre-act increases stability up to its optimum setting and, above that, again gives less stability.) In general, oscillations with a period approximately the same as those occurring at the ultimate sensitivity are due to too high a sensitivity; automatic reset gives longer periods and pre-act shorter periods.

PROCESS-REACTION CURVES

A control circuit consists of a controller and a process, the valve being considered a portion of the latter. Pen movement gives an output-pressure change, which affects the process, which in turn affects the pen. So far, we have considered control effects, the portion of the control circuit tying pen movement to output-pressure-behavior pattern. We have also considered the effect of altering this pattern on the entire control circuit, taking as evidence the pen recovery from disturbances and load changes.

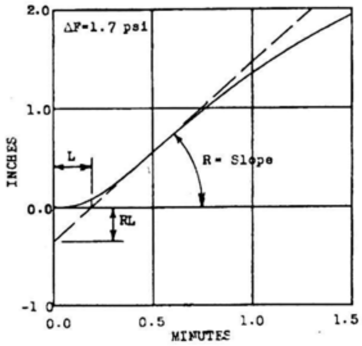

FIG. 8 REACTION CURVE

We will now eliminate the controller from the circuit, make certain output-pressure changes, and show how the resulting pen behavior can be used to evaluate controllability of the process and predict optimum controller settings.

Process-Reaction Curve. In any control circuit, there are several time lags. The lag of inflating the valve is present in all. Some time lag occurs in the measuring portion between a change at the thermometer bulb or pressure connection and the indication of that change at the pen. Added to these two may be series of lags in the apparatus under control.

The difficulty of dealing mathematically with processes involving a series of lags or even of applying values to the various lags and adding them is very great indeed. However, having a process, a pen, and a means of controlling the process (a valve), it becomes possible to get the summation of all tile lags by simply altering the valve position and analyzing the resulting curve traced by the pen.

To be more explicit, suppose that we have an application with a controller installed and cut the air line connecting the controller to the diaphragm valve. Then, if we connect an air-reducing valve to the diaphragm-operated control valve, it will be possible to apply the air pressure necessary. to hold the control valve in any. position. We will thus be able to make a change in the pressure applied to the control valve in the same manner as the controller would do it (this . can still, be called the output pressure because its effect will be the same as though it came from the controller) :and note the resulting pen behavior.

With the control circuit so arranged, we may, by applying the correct pressure to the control valve, first bring the recording pen to the desired point on the chart. If then a sudden sustained change in pressure on the control valve of F psi is made, the pen will trace an S-shaped curve which we will call a "reaction curve." Fig. 8 shows a reaction curve for the process which we have been considering.

While Fig. 8 represents a typical reaction curve, an infinite number of variations are possible. On some applications, notably liquid-level control, the curve may come to a maximum slope and continue indefinitely (or until the tank runs over). This type of process. is not "self-controlling." On others a definite dead period or velocity-distance lag exists. and the reaction curve shows no pen movement, for a finite time after the change in valve position; it then either starts at the maximum rate or builds up to the maximum.

In discussing optimum controller settings, when using pre-act response, we noted that a sensitivity between $0.6S_u$ and $1\ S_u$. could be used. The best value appears to depend upon the shape of the. reaction curve prior to the maximum slope; a lag predominantly of the dead-period type calls for sensitivities toward $0.6\ S_u$.

Optimum Setttngs From Reaction Curve

Two characteristics of the reaction curve are used to fix the proportional-response sensitivity. The "reaction rate" (*R*), i.e., the maximum rate at which the pen moves occurs at the point of inflection in the reaction curve. A line drawn tangent to this point intersects the initial pen position a certain length of time after the change in valve position. This time we will call the "lag" (*L*) of our control circuit, The optimum setting of sensitivity for a controller is inversely related to the product of' *R* and *L*, determined from the reaction curve. If the tangent line is projected until it intersects the vertical axis, the product *RL* is graphically determined, as shown in Fig. 8. Good control is generally obtained when proportional-response sensitivity is so adjusted that a pen movement of *RL* in. gives a pressure change of *F* psi.

On the reaction curve of Fig. 8, a 1.7 psi valve change was made so the optimum sensitivity setting is approximately

$$Sensitivity = \frac{\Delta F}{RL}\ psi\ per\ in.$$

Where

R = 1.7 in. per min
L = 0.2 min
RL = 0.34 in.
F = 1.7 psi

The predicted sensitivity of 1. 7/0-34 or 5 psi per in. gave curves Fig. 1(f) and Fig. 3(d). These curves were previously selected as giving good stability, that is, an amplitude ratio of approximately 0.25.

Unit Reaction Rate. No justification has been given for calling the distance L on the reaction curve the lag of the process, but there appears to be a good reason. On most processes, reaction curves, caused by different valve-pressure changes F, are similar in shape, differing only in the value of *R*, that is, the reaction rate caused by a 1 psi change is about twice as great as that from a 0.5 psi change, but the intersected distance *L* remains constant regardless of *F*.

When taking a reaction curve, it is sometimes necessary to make *F* quite small, in order to prevent undue disturbance to the process being tested. The resulting reaction rate is then converted to a "unit reaction rate" (R1), that which would be caused by 1 psi pressure change on the control valve. This is done by dividing the reaction rate found by *F*

$$R_1 = \frac{R}{\Delta F}\ \frac{\text{in. per min}}{\text{psi}}$$

The formula for a good sensitivity setting may then be written

$$Sensitivity = \frac{1}{R_1 L}\ psi\ per\ in.$$

The ultimate sensitivity will be about twice as great

$$S_u = \frac{2}{R_1 L}\ \text{psi per in.}$$

At the ultimate sensitivity, the period of oscillation is about 4L min, increasing to about 4.6L as the sensitivity is lowered to one half the ultimate.

An approximate description of the characteristics of a process is given by values,-of the two quantities unit reaction rate and lag. True, these two are only a rough measure of the entire reaction curve, telling nothing about its shape before and after the point of inflection, but they give enough of the story to allow a prediction not only, of optimum sensitivity and period of oscillation but of optimum reset rate and pre-act time settings as well.

It should be kept clearly in mind that the controller settings are determined from the reaction curve caused by an output-pressure change (control-valve-position change) and not by the reaction curve which is caused by a load change.

Reset-Rate Determination From Reaction Curve. Since the period of oscillation at the ultimate sensitivity proves to be 4 times the lag. A substitution of 4 *L* for P_u in previous equations for optimum reset rate gives an equation expressing this reset rate in terms of lag. For a controller with proportional and automatic-reset responses, the optimum settings become

$$Sensitivity = \frac{0.9}{R_1 L}\ psi\ per\ in.$$

$$\text{Reset Rate} = \frac{0.3}{L}\ \text{per min}$$

At these settings the period will be about 5.7L, having been increased, by both the lowering of sensitivity and the addition of automatic reset.

Pre-Act Time Determination From Reaction Curve. Using again the relationship between *L* and P_u we find that the optimum pre-act time depends directly upon the lag and is normally equal to L/2. This tells us that pre-act will not normally be used on applications in which the reaction curve shows a lag . smaller than 0.2 min. since the minimum pre-act time available on industrial controllers is about 0.1 min. It will be useful on all applications with lags greater than 0;2 min.

The optimum settings determined previously for all three control effects, when expressed in terms of unit reaction rate and lag, appear as follows

$$\text{Sensitivity} = \frac{1.2}{R_1 L}\ \text{to}\ \frac{2}{R_1 L}\ \text{psi per in.}$$

$$\text{Reset Rate} = \frac{0.5}{L}\ \text{per min}$$

$$\text{Pre-act Time} = 0.5L\ \text{min}$$

Control Valve Characteristics

In general, any change of a control circuit which allows a higher controller sensitivity and faster reset rate to be need used will improve the control results obtained. We have seen that the addition of pre-act response gives both of these improvements.

At times certain changes in the process can be made which allow, a higher sensitivity and reset rate.

Any decrease in the lag of a process permits an increase in reset rate and attendant reduction in period of oscillation, since the reset rate is inversely related to lag and the period directly related. Any decrease in the lag of a process if it is not attended by an increase in reaction rate permits an increase in sensitivity since the sensitivity is inversely, related to the lag. Any decrease in the unit reaction rite of a process, if not attended by an increase in lag, allows higher sensitivities, since sensitivity is inversely related to reaction rate.

Stated more concisely, any decrease in the value of R_1L increases the optimum sensitivity, and any decrease in L increases tile optimum reset rite. Also any decrease in L decreases the period of oscillation,

Some applications, as we have already noted, call for widely different sensitivity settings at different load conditions. In these cases, we have said the sensitivity must be set low enough to give stability at the most difficult load even though the control is penalized, at easy load conditions. This phenomenon is due to the fact that the unit reaction rate generally changes with load. The lag normally remains about constant. Control valves with special flow-lift characteristics have been used in an attempt to correct for this change in unit reaction rate with load. The optimum characteristics vary with the application under control and are not always "logarithmic" or "equal percentage" as is commonly thought.

PROCESS CLASSIFICATION

Since either the ultimate sensitivity and attendant period or the unit reaction rate and the lag may be used to determine optimum controller settings, it follows that the latter values may be determined from the former, This suggests that, without running a reaction curve on a process, values of R_1 and L may be determined during adjustment of the controller.

Knowing the ultimate sensitivity (Su) and the period at this sensitivity (Pu), a rearrangement of preceding equations shows how these values may be converted into L and R_1

$$L = P_u / 4 \text{ min}$$

$$R_1 = \frac{8}{P_u S_u} \; \frac{\text{in. per min}}{\text{psi}}$$

Classification of processes are terms of their unit reaction rates and lags would appear to be a decided improvement over present arbitrary methods.

CONCLUSIONS

We have proposed a system of units for measuring the control effects, which are now in common use. When using these units, the values of the sensitivity, reset rate, and pre-act time all increase as the relative valve action per pen action increases.

The lag and unit reaction rate have been introduced as a quantitative measure of the controllability of processes, and we believe they form a good basis for a classification of processes.

Formulas have been presented which enable the controller settings to be obtained from an analysis of the process-reaction curves (that is, unit reaction rate and lag).

We have presented a simple method for adjusting the controller when it is installed on an application, making use of the ultimate sensitivity and period. Having shown that the controller settings can be obtained from the, reaction curve, it will be possible for the equipment designer to calculate an approximate reaction curve for certain applications and thus determine the controller settings even before the equipment is built.

The usefulness of each particular control effect has been shown by examining its effect on the quality of control.

It been, pointed out that valve characteristics should be matched to each process so that a constant unit reaction rate prevails at all loads. This incidentally gives a rational explanation for the use of valves with special flow-lift characteristics.

Examination of pre-act response has shown that it improves control by increasing stability, reducing period, and allowing larger settings for the other responses. The relation between the pre-act setting and lag (or ultimate period) has simplified its adjustment. A summary of control effects is given in Table 1.

TABLE 1 SUMMARY OF CONTROL EFFECTS

RESPONSE	ACTION	MEASURE	UNIT
Proportional	$\frac{\text{Valve movement}}{\text{Pen movement}}$	Sensitivity	Psi per in.
Automatic reset	$\frac{\text{Valve velocity}}{\text{Pen movement}}$	Reset rate	Per min
Pre-act	$\frac{\text{Valve movement}}{\text{Pen velocity}}$	Pre-act time	Min

Note that the proportional response action may also be expressed as a valve velocity per pen velocity.

SUMMARY OF CONTROLLER ADJUSTMENTS

Determine the ultimate sensitivity (S_u) and period (P_u), or the unit reaction rate R_1 and lag L. For the three types of controllers the optimum settings are as follows:

Proportional

$$\text{Sensitivity} = 0.5 S_u = \frac{1}{R_1 L} \cdot$$

Proportional plus reset

$$\text{Sensitivity} = 0.45 S_u = \frac{0.9}{R_1 L}$$

$$\text{Reset rate} = \frac{1.2}{P_u} = \frac{0.3}{L}$$

Proportional plus reset plus pre-act

$$\text{Sensitivity} = 0.6 S_u = \frac{1.2}{R_1 L}$$

$$\text{Reset rate} = \frac{2.0}{P_u} = \frac{0.5}{L}$$

$$\text{Pre-act time} = \frac{P_u}{8} = 0.5 L$$