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Elements of Automatic Control

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Common experience is drawn upon to illustrate the problems met in connection with automatic control and the principles of operation used. An example is given of the equipment for a continuous neutralization reaction and the apparatus for carrying out the automatic control. The various kinds of time lag encountered are indicated and put under three types—capacity lag, transfer lag, and head lag. The latter is resolved into the first two.

Four basic elements of control are derived—metered control, deviation control, rate control, and damping control—and are illustrated by various kinds of automatic control equipment. A direct measure for control performance is given by determining the time required to re-establish equilibrium in terms of the total transfer time lag.

ratio P D PID

HAVE you ever tried to eliminate the fluctuations of temperature in your home? If so, you must have gone through the mental processes required to analyze automatic control problems. You deal with time lags: (*a*) the time required to build up a draft and a fire, (*b*) the time required to build up the temperature of the equipment so that the heat can be transferred to the air, (*c*) the time required for the heat to be carried throughout the house, and (*d*) the time required for your thermometer to show this new temperature value. You may not have recognized the various factors to the point where you could separate each one and determine its effect and the way to compensate for it, but you have dealt with the problems which good controllers analyze and solve.

Let us illustrate this further by referring to a neutralization reaction (Figure 1) which, to a chemist, is more easily pictured quantitatively than combustion control or temperature regulation. If one is to regulate a process for neutralizing acid with alkali, the first thing to consider is a means of measuring the rate of flow of both alkali and acid so that the two flows may be proportioned to one another. This may be done by measuring out so many buckets of each material or by means of simple flowmeters and damper control, so that for every flow of the acid a predetermined amount of alkali is permitted to pass. This principle of control may be sufficient in many instances. At any rate, it should be considered as one of the elements of control. Experience, however, indicates that it is best to check what a ratio control does by determining whether the two flows neutralize each other exactly, since concentrations may have changed.

cascade = metered

A potentiometer recorder facilitates this work considerably. As soon as you see a record of the pH of the solution leaving the mixer, you realize that automatic adjustment of the alkali should be possible. This may be done by having the valve opening while the reading is low and closing while the reading is high; but operating the control valve at a rate proportional to the deviation greatly improves the speed with which the system can be regulated and makes possible a more accurate control with greater variations in acid flow or concentrations.

P control

Many devices have been developed to carry out this deviation control. Where the response of the control mechanism to any change is very rapid and the effect of any change in flow of alkali is immediately determined by the detector, such a control system can be geared to operate rapidly and hold the value of the pH close to an exact point, regardless of changes in acid flow.

Capacity Lag

One of the first limitations of the combinations of metered and deviation control is that most chemical reactions, as well as most physical processes of heat transfer and speed regulation, have to deal with capacity, such as inventory, heat storage, or inertia. This is often called "favorable lag."

cascade.

A change in the flow of acid occurs, but for some time its effect is masked by the inventory of the mixer until the effluent gradually increases in acid concentration. Consequently, if we want to know just how much to change the flow of alkali in order to balance the flow of acid, we must wait until the entire inventory has taken on the condition indicated by the instantaneous rates of flow. Then we can proportion the alkali valve setting to the new acid flow or its change in concentration, and expect to get a fairly close setting of a new value.

As soon as we recognize this fact, however, we realize that the rate at which the indication is changing is a measure of the amount by which the acid flow has changed. The experienced operator uses this rate of change of pH as a means of anticipating the final equilibrium reading. He corrects the flow of alkali according to the trend of the indication so that the deviation from the right value is greatly reduced and his control is much more responsive. This fact was recognized and its application to automatic control commercialized many years ago, although it has not come into prominence for process control until the last four years.

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Hydraulic governing mechanisms for water turbines and steam engines were developed years ago, using this element of control, in conjunction with very responsive and powerful

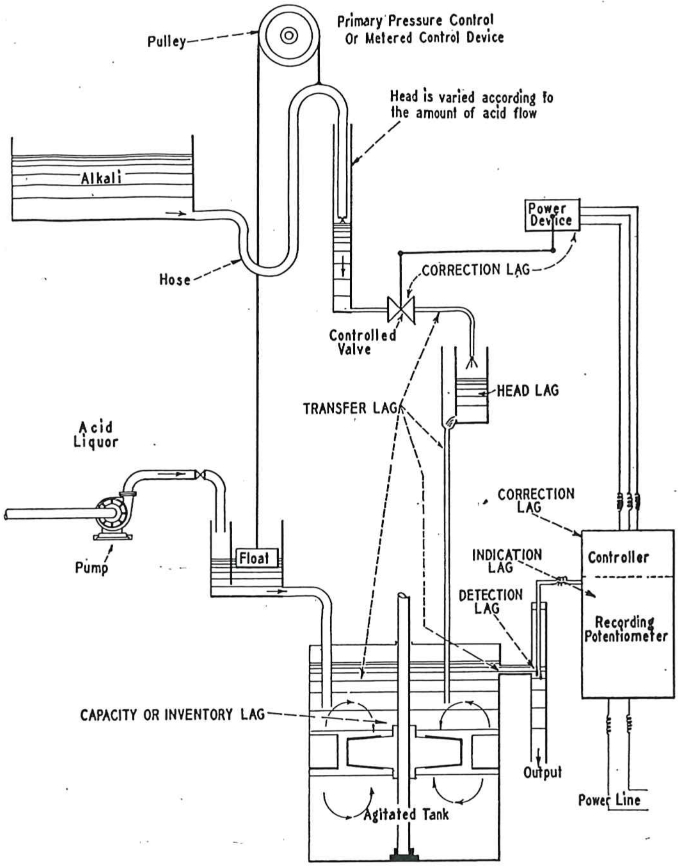


FIGURE 1. NEUTRALIZATION REACTION

deviation control apparatus, to reduce the effects of inertia and prevent hunting in power plant machinery.

Transfer Lag

Capacity lag, however, is not all one has to consider. Even the best control setup is bound to run into other kinds of time lag. First, there is the detection lag, due to the time required for the changed condition to be transmitted to the electrode or primary measuring elements. Next, there is a lag in the instrument, due to its inertia and time-consuming operating cycles in order to make the indicator or recorder follow the changes at the electrode. Time is also consumed by the controller to convert the reading of the instrument into control impulses which carry out the command of the control mechanism. Then there is the time required for the power device to respond and arrive at its next position. Finally, there is the time required for the new flow of alkali to travel through the mixing equipment and to be detected at its outlet. It is the time required to transfer the alkali from the valve to the electrode and is called "transfer lag" or at times "flow lag."

The first mentioned lags are due to the control equipment and are generally easier to hold down than the transfer lag, which is inherent in the process. All these lags are of the same nature and can be lumped together as transfer lag. Added together, they generally amount to from 5 seconds to several minutes. Obviously it is the object of good process and instrument engineering to reduce these lags to the minimum. It is evident that neither man nor automatic control equipment can do anything about a condition that is going wrong until he finds out about it, nor can he keep the condition from going too far in the wrong direction if an appreciable time elapses after starting the corrective action before its effect is felt.

The good operator who gets the "feel" of the process, recognizes the fact that it has taken some time for him to find out what is going wrong and then for the corrective action to take effect. Therefore, when he sees the pointer go down, indicating a lack of alkali supply, he opens the valve wide for just a moment to take care of the insufficient supply of alkali that has passed before he found out about the lack, and then closes the valve again to a slightly higher value, based on his knowledge of the correct valve setting for the observed deviation. Then he waits to see what happens before doing any more unless additional changes appear which require correction. This is carried out in automatic control by the damping control element. What is this? I-control? PID

Head Lag

One more troublesome lag occurs, particularly in heat transfer equipment. It is illustrated in the neutralization reaction by a head tank between the control valve and the mixer. It is caused by the change in temperature head required to increase or decrease the amount of heat transferred. For example, the primary flow is doubled so that twice as much steam should be used. However, before this can occur, the temperature of the heating elements and the pressure of the steam in the chamber must be increased to a point sufficient to drive through the additional amount of heat. It is a capacity lag due to heat and vapor storage, but it behaves like transfer lag in so far as its effect cannot be compensated by rate control but can be mitigated by damping control.

The initial control impulse given to correct the conditions must carry with it an added amount to furnish the extra head. In other words, instead of the experienced operator opening the valve two turns for a moment, he opens it three turns and then closes it back to the more correct continuous flow position in order to supply the extra heat required to increase the heat head.

Head lag is a lag of the capacity type in such a position in the circuit as to delay the action of the control. It is therefore counteracted by treating it as transfer lag.

We find, then, that there are four control principles or guides when a process is to be regulated:

1. The measure of the forces or flows that cause changes. (FF)
2. The observed deviation.
3. The amount of inertia or capacity to be adjusted.
4. The time it takes to detect changes and to make corrections effective.

These four guides are used by, and embodied mechanically in, the following four elements of control.

Metered Control

← Seems to be ratio control but...

In metered control the flow of the controlled quantity (alkali for the Dow process) is proportioned to the primary flow, independent of the end result. This principle is generally used in combustion control. It also includes the case in which a primary control is used to eliminate irregularities, such as flow or pressure changes, or to take care of starting or stopping.

Deviation Control

~~P-A~~ really P + I-action

The deviation control can be very crude and often amounts to nothing more or less than an on-and-off control which operates a valve or relay, on an open-and-shut cycle. It is sometimes improved by the use of a by-pass flow or steady current to take away the severity of the changes.

P? Other improvements in deviation control include valve opening and closing as the meter calls for more or less flow, and valve-moving mechanism, fluid or motor operated, allowing a throttling range with drift of the control point.

~~I~~ P

I

The final improvement in deviation control is to have the rate of the valve action proportional to the deviation and to have it come to rest at the same point, regardless of the total flow or load. In effect, it accomplishes the result of a simple direct-acting float control, in that the valve position follows the integral of the deviation but without droop.

Rate Control

D-action

The action of rate control is proportional to the rate of change or the first derivative of the indication. It is added to deviation control, or to the combination of metered and deviation control, in order to increase the speed of the correction when the indicator is moving away from the right value at a rapid rate and to anticipate overshooting when the indication is approaching the right value at a rapid rate.

This rate control also runs through a whole range of refinements. Sometimes it is crude, as in the case of a temperature control where the effective temperature around the control unit is modified by placing the thermostat near the source of heat or refrigeration. Sometimes the control point is slowly oscillated to prevent overshooting. In the best type, the sensitive element actuates the control, not only according to the actual position the indicator has reached but also according to the rate of change.

The combination of these three principles can be made to do good work on most control jobs, especially if the capacity lag is sufficient to iron out fluctuations due to the transfer lag.

Damping Control

~~I-action~~ ~~PID~~ Not clear what this is

This control should have in it the ability to overemphasize and then reverse and wait for a time depending on the amount of the transfer lag.

This method of control also has a whole range of gradations or refinements. The crudest form is the "kicker," in which an arbitrary overshot is passed momentarily to make up for part of the undercompensated flow that has passed the valve between the time the change occurred and the time the detector could finally do something about it. Delayed-action damping properly proportioned in amount and time makes it possible to obtain the benefit of an intermittently operated control, and yet have the apparatus able to respond to any new changes that come about during the period when it would otherwise be ineffective.

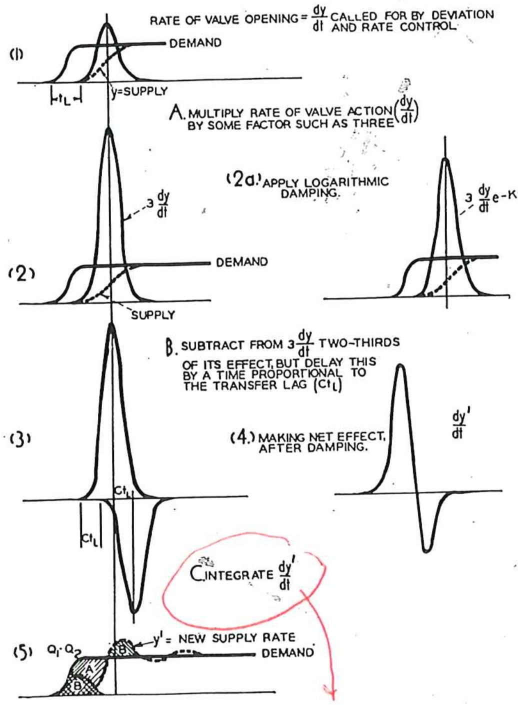


Figure 2. Evolution of Damping Control

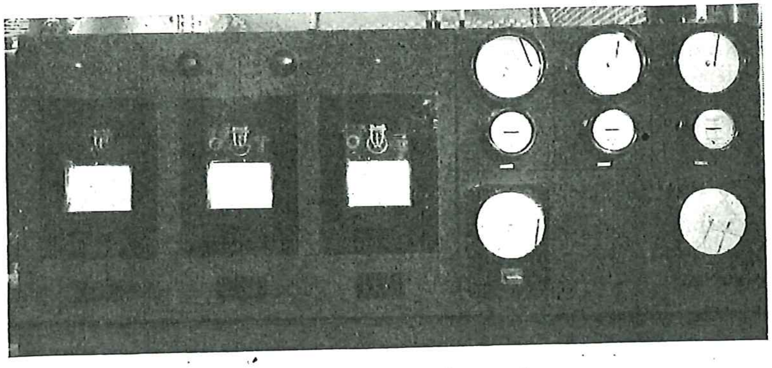
Quite complicated!

A simple way to determine the difference between rate control and damping control is to realize that the first is primarily sensitive to the rate of change. It is capable of changing the control point so as to anticipate the condition that will come about when the changes that have been made will have had time to affect the inventory of the system. The transfer-lag compensator acts to give an increased flow for a period of time proportional to this lag, regardless of the

Table I. Grading Chart for the Four Basic Elements of Control

Control	Metered	Deviation	Rate	Damping
Action	Ratio control, proportioning control, pressure control, integrating control, level control; overcomes outside variables, meters flows	Proportional control, floating control, throttling control, modulating control; corrects variations from fixed balanced point	Process lag compensator, anticipatory control, storage lag pacer; compensates for capacity lag (starting time)	Detection, indication, apparatus and correction lag compensator; mitigates effect of transfer lag
100 per cent; A = all that is available	Proportional to rate of change + rate of flow + state of inventory	Noncorresponding throttling control + reset, point control; floating control with droop corrector	Rate of change control; differential bellows motor; follow up with reset spring	Smoothed-action damping control; impulsator
60 per cent; E = elemental form of the factor	Proportional to demand or rate of flow + state of inventory	Throttling control, step control; drooping characteristics	Modulating or trend analyzing using steps	Impulsator, overemphasizing changes momentarily
30 per cent; I = imperfect, inaccurately proportioned	Proportional to amount of inventory—i. e., pressure, tank level	Opening-closing; on-off; high-low; open-shut	Roughly modifying indication or control point to emphasize changes	Kicker, arbitrary slugs or intermittent operation
0 per cent				
O = omitted	Rating O is given for any one factor not in the control system			
U = unsatisfactory because of defects	Rating U is given for any one factor that is represented in a manner to increase the difficulty of control—i. e., instrument time lag, friction, disturbing influences not properly shielded or compensated			

amount of capacity lag. Depending on conditions, it frequently calls for less and reduces the valve opening to a smaller flow after having passed a compensating slug while the indication or meter still is on its outward excursion and calling for increased quantities.



Instrument Panel at a Water Softener

The first three elements were discussed and illustrated in a paper (*1*) which was later rewritten by Olive (*2*). Figure 2 supplies the graphical steps required to explain better the resulting properties of damping control.

Combination of Control Elements

Obviously each of these control elements can be incorporated in apparatus of many types and forms. Turbine governor work has led to powerful and responsive hydraulic devices. Gas control work has led to air-pressure-operated units that are very sensitive and, at the present time, highly developed for process control. They have the handicap of dealing with a compressible fluid that often introduces correction lag. However, they compensate for most of this fault by very little indication lag. The development in this laboratory has been along the line of electrical power control devices. All three types have their place, particularly when they are operated by sensitive controls used to pilot or relay the main flow of power.

Although at present only one manufacturer appears to incorporate the four elements of control in a single system where the best results are desired, it is reasonable to say that within another four years engineers in general will realize that it does not pay to waste time with anything but the best. With the increased demand, apparatus that incorporate all these features in their highest developed form will be available on the market, undoubtedly for less cost than the relatively incomplete and unsatisfactory equipment now being used in industry.

Tc

Happily, there is one single property other than mechanical reliability that evaluates the performance of an automatic control system. It is the measurement of the time in terms of the amount of transfer lag required for the apparatus to arrive at a close approximation of the right setting after a disturbance has occurred. A good control will be capable of operating fast enough to establish equilibrium conditions within less than twice the total transfer lag. Experience in this laboratory has shown that this is not too much to expect, although it is a high standard for control instruments in general. Where capacity lag is a big factor, it should be added to the transfer lag to the extent of about one-tenth of its actual duration.

Anyone who has developed automatic control equipment step by step is amazed at the increase in speed of operation and response of an automatic control when adding successive control elements to the system, and also when the equality of each of the control elements is improved.

For example, a valve that can be operated at such a speed as to go from full open to shut position in 20 minutes when operated by an opening or closing control (rating about 30 per cent under deviation control) may be speeded up to accomplish the same result in 20 seconds when the best type of deviation control is used, to which has been added rate and damping control, and yet not produce as much hunting as it did when operated on the extremely slow 20-minute speed. When metered control is added, the primary flow can be shut off completely and within several seconds the secondary flow is also shut off. With this combination, large variations in the primary flow hardly affect the reading of the final condition, since the two flows are roughly proportioned, or one of them is brought to a fairly constant value before they interact.

Table I was first used for correlating twelve types of controls described by Smith (*3*). A control setup rating 100 for each of the four elements (400 in all) is much more than thirteen times as good as a control rating 30 under metered control or under deviation control. On account of the difficulty of evaluating a given control unit in exactly comparable percentages in Table I, *A* is chosen to stand for the best possible, *U* for unsatisfactory, *O* for an omitted element, and the other vowels, *E* and *I*, for intermediary grades.

The best control system is one that is so well regulated by metered control and so quick to smooth out slight deviations, that it appears to be doing nothing.

ratio

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"The research man ought to be thought of as the fellow you keep up in the crow's nest to see beyond your horizon, to tell you where there is another prize ship to be taken or a man of war to be avoided."

This is fairly complicated and confused.