

Designing INDUSTRIAL

Electronic computer is adjusted to simulate an industrial operation and its control. Engineer then manipulates system to determine optimum design. To simplify computer construction and increase speed very fast time scales are used in computing circuits

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USE OF ANALOGS makes it possible to experiment readily with devices or phenomena under changes of scale or after transformation of their variables. All models, whether they are the small-scale replicas used by civil engineers, model airplanes in the wind tunnels of aerodynamic engineers, miniature boat hulls in the towing tanks of naval architects, or the equivalent circuits used by acoustical engineers to study microphones, are analogs. Dynamic analogs can be highly complex assemblies such as differential analyzers, abstractions such as mathematics itself, or direct simulations of the process.

The great advantage of analogs as devices for solving engineering problems is that they are simple. Electrical analogs of mechanical, thermal, or other systems can be assembled and adjusted quickly and easily. For example, in designing a pneumatic control, the analogous electrical network of resistors and capacitors of Fig. 1A was built. As a suitable design evolved from experiment a more formal network was constructed. Finally, after experience in the laboratory under many control circumstances, the actual pneumatic control of Fig. 1B was built. Much time and costly machining were saved using the easily modified electrical analogy.

To facilitate making electrical analogies and to perform the broader functions of analog computers in problems dealing with automatic controllers, the Analaut has been developed. It is a flexible electronic instrument for study and demonstration of regulatory systems such as industrial process con-

trols, servomechanisms or position followers, navigational controls, and stabilizers for power plants.

Designing Controllers by Analogs

As long as a process remains in the steady state its analysis is relatively simple. About two decades ago engineers in the process industries, particularly those concerned with instrumentation, became concerned with the dynamic nature of their processes and equipment, especially under automatic operation. Owing to the complexity of such problems, early studies were empirical. Mathematical analyses

and syntheses of idealized systems were made. Hydraulic analogs of thermal systems were built from which transient behavior could be studied readily by direct measurement.

Beginning in 1936 the writer developed a complete computational Automatic Control Analyzer based on interconnected high-speed models of both process equipment and its associated controller, which took the form shown in Fig. 2A. Different masks depicting the processes and controls being studied were superimposed on the panel to facilitate visualizing the system; the in-

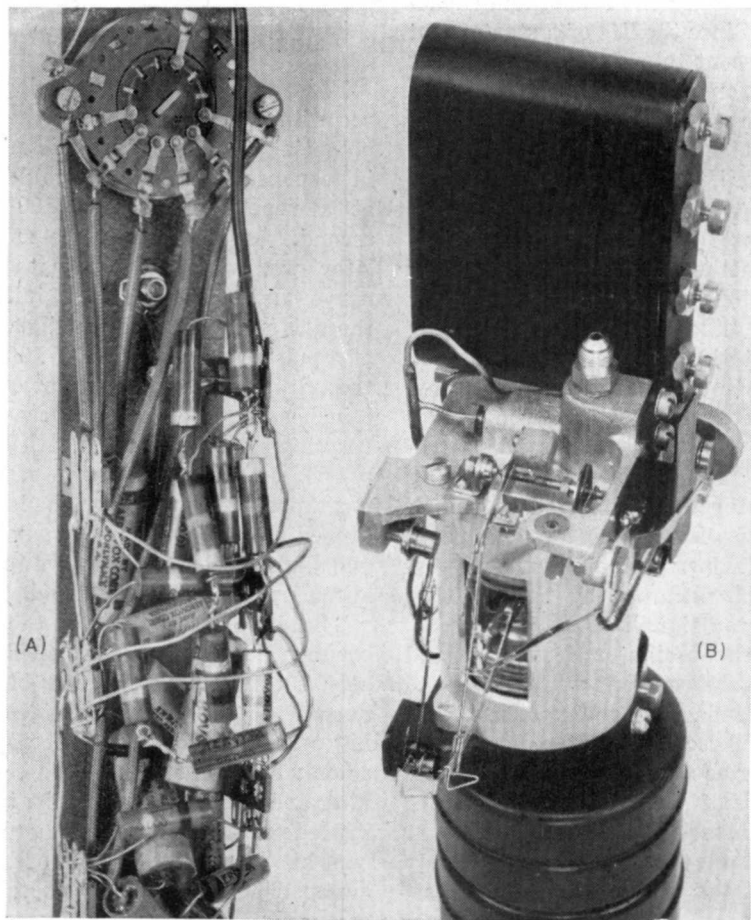


FIG. 1—Electrical analog (A) simplifies design of pneumatic controller (B)

CONTROLLERS By Analog

strument is still in use. The same basic technique, developed to a higher degree, is employed in the modern instrument shown in Fig. 2B. It is used for designing controls and also for predicting the necessary type of control for a proposed installation and the adjustment for optimum performance of complex systems.

Whereas controllers can be designed by mathematical analysis provided the system is not prohibitively complex or by testing in the completed plant if adjustments to the system can be made safely and economically, it is simpler to represent the closed control-process loop by an analog. The heavy lines of Fig. 3A show the loop whose properties are to be studied; the rest of the diagram shows the elements of

the analog analyzer. The control manipulates the plant input m in recognition of the unbalance u so as to cause the regulated variable v to follow its desired value v^* , thus reducing the absolute value of the unbalance u to a minimum near zero. All the variable and parameters in the analog are the counterparts of those in the actual plant.

In the analog computing system, the controller and the plant are represented by electronic model assemblies, a basic circuit of which is shown in Fig. 3B. The essential loop variables are transformed into measurable voltages, each of which can be related to the corresponding plant variable by an appropriate scale factor such as pounds per square inch per volt (to convert to pressure in a pneumatic control).

For representing the desired value there is a manually adjustable steady component and an optionally inserted variable component for disturbing the system. The flexibility of the instrument permits comparing controlled and uncontrolled responses of the simulated system, studying hysteresis and excursion limit effects, inserting conventional regulating functions with proportional, derivative, integral, and second integral effects, and inserting special features from external circuits. Response of the analog is determined by disturbing it with a recurrent pulse and observing the transient on an oscilloscope. The time scale of the analog is made short so that the loop will have returned to equilibrium before the next pulse and so that the computing elements, especially the capacitors, can be conveniently small. The disturbance can be inserted at any desirable point in the loop.

Usually the variations around the simulated loop are displayed as functions of time on the oscilloscope, with suitable timing markers if necessary. However, by plotting one variable against another parametric plots of great interest can be obtained. Figure 4 shows curves plotted against time, and a parametric curve (for a more complex system) by way of comparing the two types of displays. The parametric method shows the stability and phase relations among significant loop variables.

With such an analog of the process an analog of the appropriate controller can be developed and its suitability observed from the transient response obtained. By manipulating plant or control parameters that are likely to vary during operation, critical conditions can be found and evaluated. With this information the control is practically designed. The fast operating time of the analog permits observing the complete transient response as an adjustment is made, so that a com-

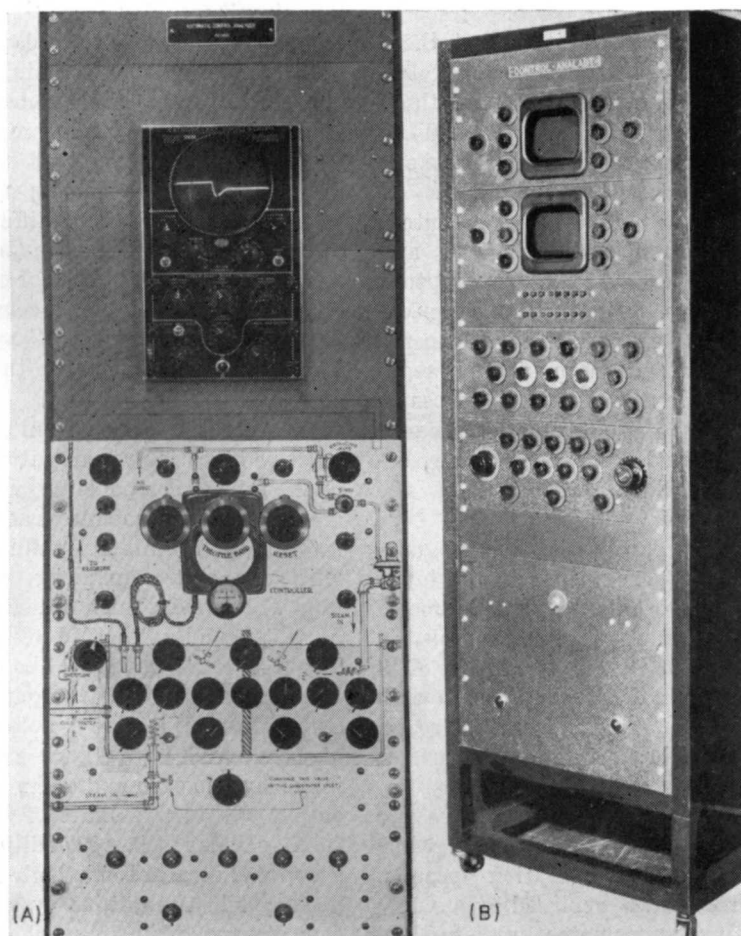


FIG. 2—Circuits of analog computer simulate plant and controller

plete study of a system can be completed quickly.

Basic Circuit

For special purposes the analog might be arranged differently than the one described here, but the same basic circuit can be used. Most of the complete analog system is based on conventional electronic techniques and so need not be reviewed. However, it should be pointed out that, of the possible mediums for building analogs, the convenience and flexibility of electronic circuits makes them excellent for experimental purposes. If one stays well above the noise and drift thresholds, there is no practical limit to the precision that can be obtained if the needs justify the effort. At the opposite extreme, tube noise can be employed for random excitations where statistical evaluations are to be made.

Figure 3B shows a useful general-purpose circuit for use in electronic analogs. Considered as an amplifier, the circuit is directly coupled for handling direct current but can operate to frequencies that are high compared to the fundamental frequency employed in the disturbance. The input impedance as seen from e_1 is very high. The internal impedance of the circuit is also relatively high so that for reliable results substantially no current can be drawn from the out-

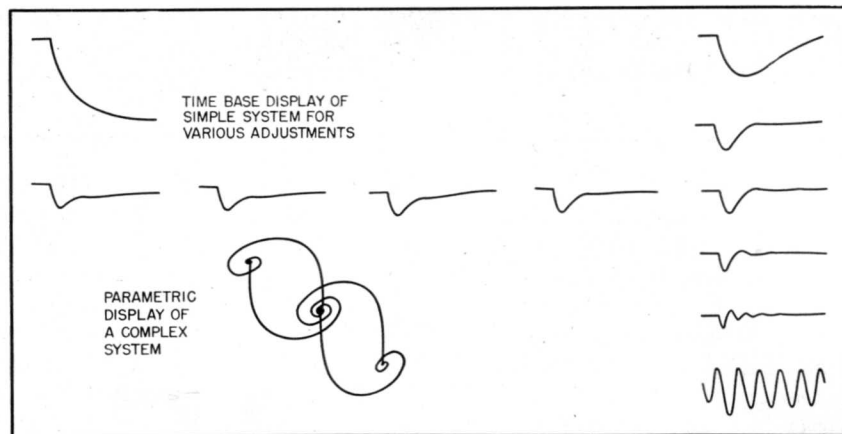


FIG. 4—Reproduction from oscilloscope tracings show how optimum response of plant can be determined by systematic adjustment of various controller adjustments

put by the load. Thus, because no current can be drawn at the output e_2 , the circuit is usually followed by another of the same kind.

A fixed source of screen excitation is provided, giving constant gain to zero frequency. The same voltage source provides a reverse current mode of operation in the computing portion of the circuit. Dropping-resistance R is chosen near the average effective d-c plate resistance of the tube. A peculiarity of the circuit is that there are no paths from the tube electrodes to ground other than those through the elements Z_1 and Z_2 , thus the currents through these elements are equal and opposite. As the grid voltage approaches cutoff, current circulates through Z_1 and Z_2 in that order, making the output e_2 positive. At the opposite extreme, the current circulates in the reverse direction making e_2 negative. Because the voltage across Z_1 follows e_1 , the output e_2 is dynamically related to e_1 in a manner dependent almost entirely on the values of Z_1 and Z_2 .

If Z_1 is purely resistive, the current in Z_2 corresponds to the input voltage e_1 . This property is useful in various ways; for example, Z_2 can be the input terminals of a four-terminal filter, in which case the current into the filter is directly manipulable with no expenditure of input energy.

If Z_2 is also purely resistive and equal to Z_1 , reversal of sign or "minus one" operation results. With Z_1 and Z_2 replaced by a single linear potentiometer, a distortionless inverting amplifier having a

useful adjustment is obtained. With the tap in the center, the gain or transfer function is nearly unity. Deflection of the tap in one direction gives a transfer or gain of G and an equal deflection in the other direction gives a gain of $1/G$.

With Z_1 still purely resistive, if Z_2 is purely capacitive, the circuit is a reasonably good integrator with a time constant $R_1 C_2$. In the control analog computer for which this circuit was developed, the computing interval is typically four milliseconds, so that the time constant of the integrator can be made long compared to the computing time using components of reasonable size. If the elements are reversed the circuit is a differentiator. In fact there are numerous dynamic characteristics that can be obtained using different combinations of impedances for Z_1 and Z_2 . The nominal equation for the circuit is given in Fig. 3B.

In operating the circuit, care must be taken to prevent saturation of the tube or components. For example, a typical fast integrator will integrate to a limit in a millisecond with one volt remaining on the input. However, such a device can be tested and calibrated by applying a square wave of about five volts amplitude to the input, with an additive adjustable d-c bias. The bias can be set to bring the effective input level to zero and will keep the output within the limits of saturation. Under these conditions a sharp and straight sawtooth will be produced in the output by a sharp square wave at the input; the amplitude of the output will be dependent

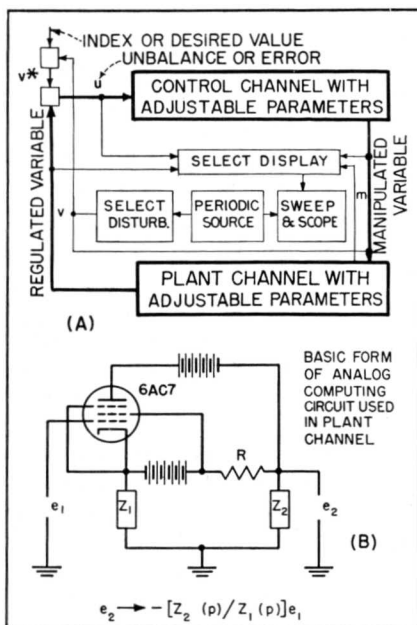


FIG. 3—(A) Block diagram of automatic control computer, and (B) basic circuit of used in the analog computer elements

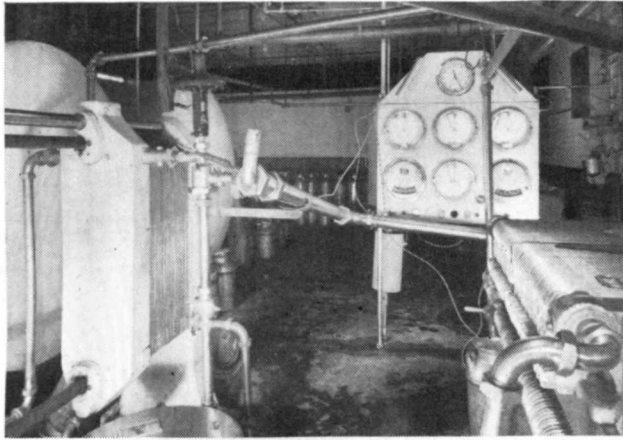


FIG. 5—Control for heat exchanger in this pasteurizing plant was designed by means of electrical analogs

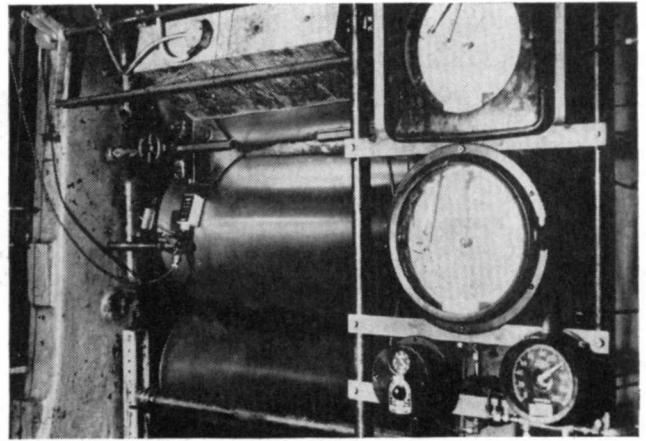


FIG. 6—Floating thermometer head on plastic calendering roller actuates automatic process controller

on the amplitude of the input, its period, and the time constant of the integrator. Other types of computing networks require other techniques for calibration and adjustment, but this example illustrates the simplicity of the methods.

The combinations possible with this basic circuit provide a powerful general technique for constructing computers and control analogs. Most dynamic conditions can be reproduced with this circuit and combinations of passive networks. For a small project, or for initial experimentation, the basic circuit using batteries is especially appropriate because well-regulated power supplies are unnecessary. As used in the control analog computer, common power supplies and auxiliary switching and calibration circuits are necessarily added to the basic circuit.

Industrial Applications

The first step in using the analog computer for designing an automatic control for an industrial plant or process is to reduce the actual system to its electrical model. In many processes it is possible to recognize the electrical analogs from the equipment and to compute parameters from known data or by simple tests. Distributed parameters can usually be represented to useful accuracies with a few lumped sections.

As mentioned above, if a direct approach is not feasible the dynamic response of the plant can be determined by introducing a known disturbance at the input or manipulated variable and observing the

disturbance produced at the output or regulated variable. The plant must remain in a sufficiently undisturbed condition, aside from the intentional disturbance, or the measurement must be repeated often enough to eliminate random effects. Where the response depends on the condition of the load or there are other nonlinearities, a series of tests may be necessary. The record of plant response is then duplicated to a much faster time scale on the control computer, with especial attention to duplicating delay and the initial portions of the response. Once the plant response has been provided in the analyzer, the appropriate control can be quickly determined.

Two typical problems illustrate more specifically how the analog method of designing controllers is carried out in practice. Figure 5 shows a portion of a high temperature pasteurizer; the main heat exchanger is at the right and the instrument panel in the near background. Several interlocking controls are included in the plant to assure holding every drop of milk at a maximum temperature for a minimum interval, avoiding overheating. The crucial regulation problem is to control the hot water temperature in the final milk heater stage at a point chosen for its significant relation to the milk temperature by manipulating a steam valve elsewhere in the system. Under manual operation with water replacing the milk to avoid accidents, a record was made of the temperature variations resulting from a sudden known change of the

steam valve. From this information the settings for a proportional derivative-integral control were determined on the analog computer. High performance was obtained from the predicted settings and further adjustments were unnecessary.

In another type of problem the crucial regulated variable was the surface temperature of the central roll of a plastic calender. The temperature was measured electronically by the floating head shown in Fig. 6 and recorded on a self-balancing capacitor bridge instrument. The manipulated variable was steam pressure under control of an auxiliary or cascaded regulator. By making a manual change in the steam pressure, the plant response was obtained on the temperature recorder. The analog of the plant was then set to duplicate this response and several control methods studied. The best type control mechanism thus determined was installed and set to the predicted dynamic adjustments, giving satisfactory control immediately.

Besides providing a design and operating tool in the field of automatic control, this type of analog has also proved useful in instructing plant personnel and as a college lecture room demonstrator and laboratory test set. Acknowledgement is made to the engineers of The Foxboro Company for whom the early developments of these techniques were made, and to Prof. J. A. Hrones of MIT for encouragement in their application to the pedagogy of automatic controls.