numbers of solutions rather than for accurate computations. No repetitive analyzers with component accuracies better than about 1 per cent have been constructed. In reality, the limitations of the cathode-ray tube indicators as such need not stand in the way of developing repetitive analyzers capable of good accuracies, since it is possible to view the solutions on the cathode-ray tube screen and then to record selected solutions accurately by means of a photographic recorder of the electromagnetic or crystal oscillograph type (see Sec. 7.3). These recorders are capable of accuracies of better than 0.5 per cent. Because of the great convenience and speed of operation of repetitive analyzers, it is to be hoped that more accurate machines of this type will be developed. Such developments are predicated mainly on the design of more accurate function generators and multipliers capable of high-frequency operation.

Resetting Methods. The repetitive d-c analog computer must contain provisions for making the computer inoperative for a brief period between 30 and 100 times a second in order to permit the introduction of the correct initial conditions for all machine variables. The methods described in Sec. 7.1 for introducing initial conditions by charging all integrating capacitors to the desired values are applicable to repetitive computers if sufficiently quick-acting relays such as Western Electric mercury relays,[1] synchronous vibrators, or even rotating switches are available.

An alternative method is to return the output voltages of all integrators to zero between successive computer runs and to include provisions for adding to the output voltage of each integrator a step-function voltage whose value corresponds to the desired initial condition. This latter method has been used most frequently with repetitive computers. It is especially applicable to studies of damped vibrations where each machine variable has a tendency to return to zero during the course of the solution. In such cases, it may not even be necessary to discharge the integrating capacitors at the end of each computer run.

The Design of Repetitive D-c Analog Computers. The design problems encountered in developing repetitive d-c analog computers are best illustrated by a discussion of existing installations.

The Philbrick Computer. The only commercially available repetitive analog computer was developed by the George A. Philbrick Researches, Inc.[2]

The computing elements of the Philbrick analog computer are mounted in small utility boxes and can be set up in a rack and connected to a "central unit" cabinet which contains the power supplies as well as various signal generators and the control circuits.

[1] Type D 168 479.

[2] Boston, Mass.

The following *linear computing elements* (operational amplifiers) are available:

1. Coefficient setting units
2. Summing amplifiers
3. Integrators
4. Differentiators
5. "Augmenting differentiators" [transfer function $(1 + aP)$]
6. "Augmenting integrators" $\left[\text{transfer function } \left(1 + \frac{1}{aP}\right)\right]$
7. "Unit lag" or "time-delay" units $\left[\text{transfer function } \left(\frac{1}{1 + aP}\right)\right]$

The following *nonlinear computing elements* are based on diode characteristics (see Sec. 6.7) and are especially suitable for the analysis of automatic control systems (see also Section 3.3 for a discussion of such circuits).

1. Limiters
2. Inert zone units
3. Hysteresis or backlash units

In addition to these computing elements, universal function generators also based on diode characteristics (see Sec. 6.7), quarter-square multipliers based on diode characteristics (see Sec. 6.1), and a number of computing elements simulating special control components have been introduced.

The voltage range used for the machine variables in the Philbrick analog computer is between plus and minus 50 volts. Overloads are indicated by means of neon bulbs. The nominal accuracy of all computing elements is between 1 and 2 per cent of full scale.

Figure 8.6 shows the block diagram of a typical Philbrick operational amplifier. The operational amplifier is of the conventional parallel-feedback type (see Sec. 4.6), but all input voltages are applied through cathode followers in order to obtain high input impedance and to eliminate possible interaction between computing elements. Every Philbrick computing element contains a phase inverter, so that both positive and negative output voltages can be obtained. Each Philbrick operational amplifier must be balanced in the usual manner (see Sec. 5.1) so as to show zero output voltage at each of its two output terminals for zero input voltage; d-c amplifier drift can introduce errors as in other d-c analog computers.

Introduction of Initial Conditions. The Philbrick analog computer will generate solutions periodically at a normal repetition rate of 60 cps. In many problems involving damped oscillations, all machine values return to the value zero in the course of the solution, so that all integrating capacitors will be discharged at the end of a computer "run." One can then introduce initial conditions by simply adding a step-function voltage equal in value to the desired initial condition to the corresponding machine variable at the beginning of each computer run. In the Philbrick analog computer, this is achieved by means of the ordinary summing amplifiers, the step functions being obtained from a square-wave generator in the central unit. If, on the other hand, one or more machine variables do not return to zero at the end of a solution, it is possible to short-circuit the integrating capacitors effectively at the end of each computer run by means of an electronic switch arrangement in the central unit. The discharging process may take as much time as a computer run. In this case, solutions are generated at a repetition rate of only 30 cps, alternate cycles being used for discharging the integrating capacitors.

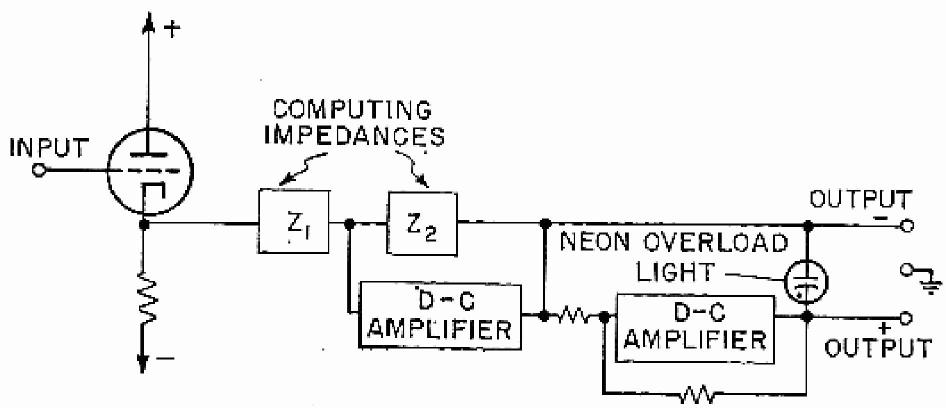

FIG. 8.6. Typical Philbrick operational amplifier.

Auxiliary Equipment. The central unit of the Philbrick analog computer contains plus and minus 300-volt power supplies, a square-wave generator for generating initial condition voltages and step voltages, a sine-wave generator for generating sinusoidal functions of the time, and a random noise generator. A sweep generator provides linear sweep voltages for the cathode-ray oscillographs used to display the solutions, and an electronic switch permits the display of two variables on one oscillograph screen. The electronic switch could also be used for certain switching applications during the computation.

Discussion of the Philbrick Analog Computer. In spite of its relatively low accuracy, the Philbrick analog computer can be an invaluable aid in engineering planning and design, especially in the development of automatic control systems.

Although the use of cathode-follower input circuits eliminates amplifier loading and interaction between computing elements, such arrangements also tend to decrease the computer accuracy. The Philbrick computer makes use of d-c amplifiers with their attendant difficulties of operation, although the repetitive solutions need not actually contain a d-c component. The newer MIT repetitive differential analyzer represents a significant improvement in this respect.

The MIT Repetitive Analyzer. A new repetitive differential analyzer was developed under the direction of Dr. A. B. MacNee[1] at the Research Laboratory of Electronics of the Massachusetts Institute of Technology.[2] This machine comprises parallel-feedback integrators and summing amplifiers as well as function generators of the photoformer type (see Sec. 6.5) and the crossed-fields electron-beam multiplier (see Sec. 6.1), newly developed by the same group. Initial conditions are again introduced by resetting all machine variables to zero at the end of each computer run and by adding step-function voltages corresponding to the initial conditions to each integrator output at the beginning of each computer run. The accuracy of the initial model is comparable to that of the Philbrick computer.

The significant improvement in the new analyzer is the use of a-c amplifiers in all operational amplifier circuits and other computing elements. Figure 8.7 shows a simplified diagram of an a-c amplifier used in the MIT computer. At the end of each computer run, all machine variables are reset to zero and all charges are removed from the coupling capacitors by means of electronic switches based on the clamping circuits commonly used in television sets.

At the end of each computer run, positive and negative *gating pulses* applied at the appropriate points shown in Fig. 8.7 permit the diodes to conduct and will reduce the output voltage of each amplifier stage (measured at the points x) to zero if the relative magnitudes of the positive and negative gating pulses are adjusted correctly by means of the balancing controls shown.

The use of these clamping circuits assures the return of the machine variables to the correct initial values for all types of solutions and also tends to simplify the computer design. Repetitive analyzers, such as the Philbrick computer, which make use of d-c amplifiers still require regulated power supplies in order to avoid drift in the reference level of the solutions. In repetitive analyzers using a-c amplifiers such as the MIT repetitive computer, power-supply regulation is not an essential requirement. Interaction between computing elements through the power sup-

[1] MacNee, *op. cit.*, p. 1315.

[2] Cambridge, Mass.

plies of repetitive computers can be eliminated by the use of conventional decoupling filters.[1] Furthermore, the a-c amplifiers used in the MacNee type of repetitive analyzer could be operated with a single power supply,

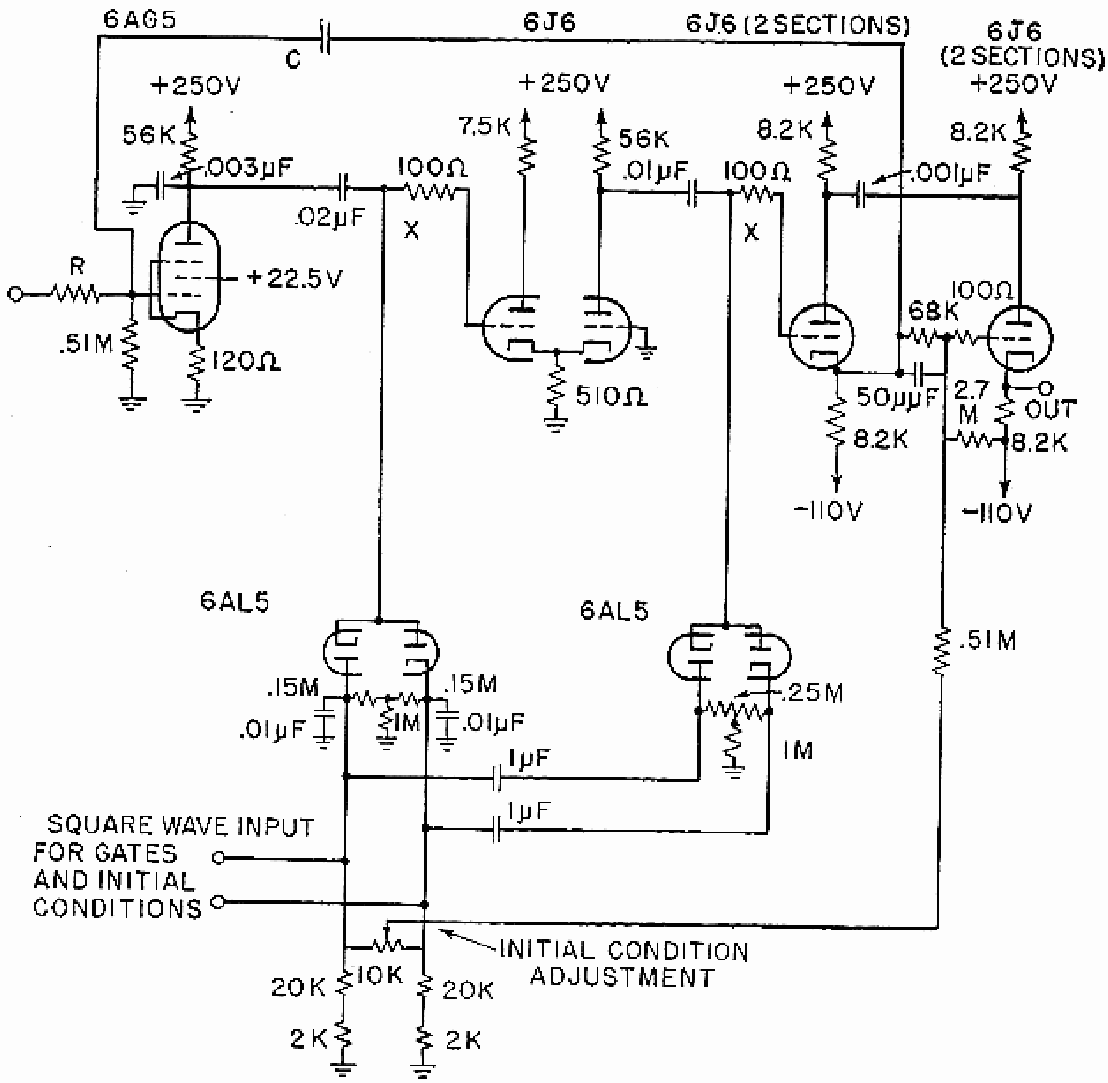

FIG. 8.7. Circuit diagram of an integrator from the MIT repetitive computer. Note the clamping circuits, used to discharge the integrating capacitor, and the summing circuit, used to add initial condition voltages to the integrator output voltage. The initial condition voltage is *not* used to charge the integrating capacitor directly in this arrangement.

although this is not the case in the original design. The component accuracy of the MacNee machine is between 0.5 and 1 per cent.

8.6. Larger Computer Installations. *Introduction.* The following descriptions of some representative larger d-c analog computers built in the United States will serve to illustrate how different designers have attempted to deal with the design problems previously discussed.

[1] See F. E. Terman, *Radio Engineers' Handbook*, McGraw-Hill, New York, 1943, for a discussion of decoupling filters.