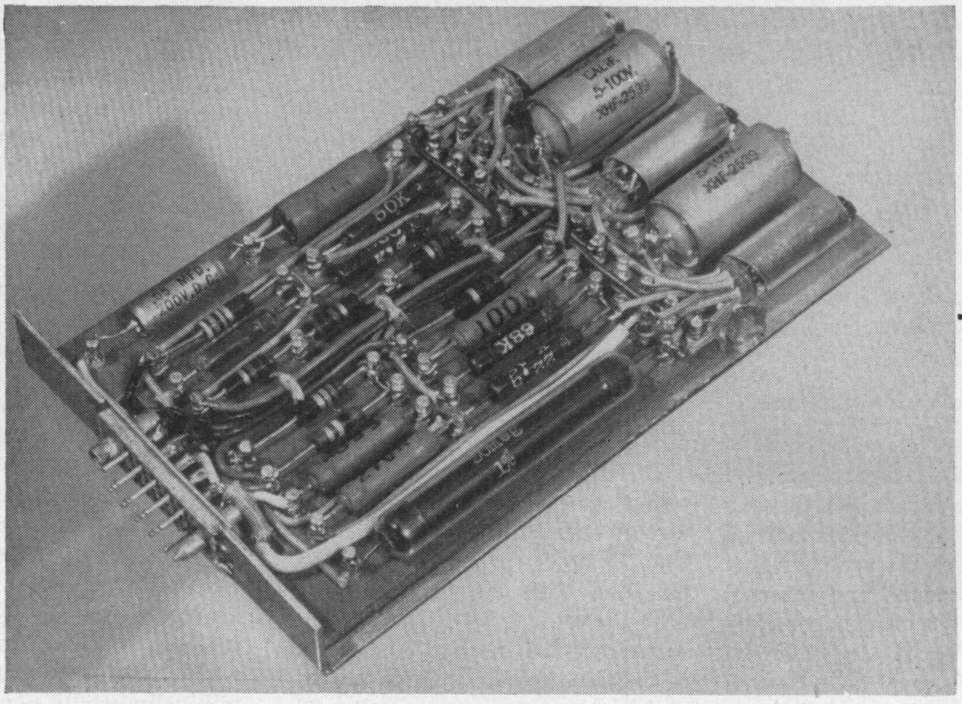

Pulse amplifier uses three subminiature tubes. Shielded input lead and input grid lead are joined on insulated stand-off terminal at lower right of board to eliminate terminal board leakage

Time-Shared Amplifier

To maintain zero output for zero input in d-c amplifiers used in analog computers special techniques or auxiliary devices are usually employed to reduce drift.

The operational amplifier[1], circuit shown in Fig. 1, is a high-gain wide-band d-c amplifier having a zero d-c output level for zero input. The short-circuit transfer impedances z_i and z_f of the input and feedback networks are frequently complex in nature.

Impedances are selected to give a desired transfer function according to the equation

$$\frac{E_{\text{output}}}{E_{\text{input}}} \cong \frac{Z_f}{Z} \qquad (1)$$

One of the most common methods of zero stabilization connects an inherently drift-free chopper-amplifier to the d-c amplifier input[2]. The rectified and filtered chopper-amplifier output zeros the amplifier. Zero offset or drift is reduced by a factor approximately equal to the d-c to d-c gain of the stabilizing amplifier.

Motor-driven rotary sampling switches have been developed for commutating a single stabilizing amplifier among several operational amplifiers.[3] The input section of the switch samples each summing junction in sequence. The output section of the switch is synchronized with the input, connecting the output of the stabilizing pulse amplifier to the individual amplifiers through low-pass filters.

R-C Amplifiers

If a simple resistance-coupled amplifier is employed as a pulse amplifier, interaction between the operational amplifiers may be caused by the time constants of the coupling capacitors in the pulse amplifier.

If one of the computer operational amplifiers is overloaded its summing junction frequently assumes a relatively large voltage. When the sampling switch contacts this junction, the pulse amplifier is overloaded and may be usable to recover in time to handle succeeding pulse samples from other summing junctions. A cumulative process results in which all the operational amplifiers loose stabilization and saturate. It is then difficult to locate the amplifier at fault.

D-C Pulse Amplifier

A direct-coupled pulse amplifier suitable for application as a non-overloading stabilization amplifier is shown in Fig. 2 and in the photograph. It employs three subminiature tubes.

Since there is no blocking capacitor at the amplifier input, grid cur-

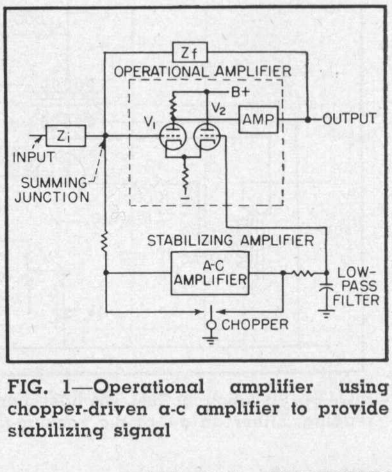

FIG. 1—Operational amplifier using chopper-driven a-c amplifier to provide stabilizing signal

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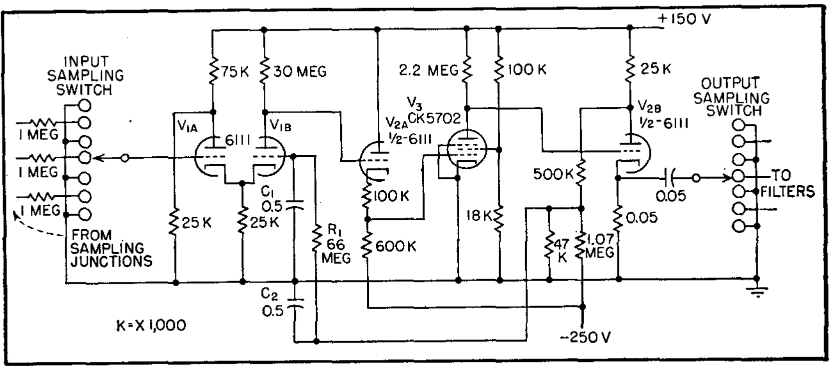

FIG. 2—Direct-coupled amplifier circuit has starved input stage to limit grid-current draw on operational amplifier summing junctions. Resistors are 1-percent deposited-carbon type. A 5-rpm, 60-contact Applied Science Corp. switch is used for input-output sampling

Quick recovery d-c amplifier furnishes zero-point stabilization to 30 operational amplifiers used in analog computer. Interaction between amplifiers can be held to less than 2 millivolts by circuit and filter design techniques

Stabilizes Computers

rent is drawn by the input tube $V1_A$. This current flows through the resistor used to isolate the summing junctions from the switch contacts. The resulting voltage drop is equivalent to an error input signal of that amount. To reduce grid current to a negligible value, a starved input stage is employed.

Starved Input

The input stage has a heater voltage of 5 volts instead of the usual 6 volts, a plate voltage of 35 volts and a plate current of 5 microamperes per section. The input stage employs a cathode-coupled circuit so that net phase reversal through the pulse amplifier is 180 deg, as required. The gain of this stage is 8 or 9.

A cathode follower V_{2A} couples the starved amplifier into the pentode amplifier stage V_3 to avoid loading effects. The output stage V_{2B} is also a cathode follower.

The overall gain of the pulse amplifier is about 1,500. With this much gain in a direct-coupled amplifier, some way must be provided to prevent the last stage from being driven to cutoff by drift in the operating point of the first stage. Amplifier d-c gain is reduced to about 20 by d-c negative feedback to the grid of V_{1B}. Pulses that the amplifier is designed for are amplified at full gain because they are eliminated from the feedback path by the filter $C_1R_1C_2$.

The filter causes a small amount of pulse overshoot. Since the overshoot generated by a given pulse sample is still decaying when the next channel is sampled, overshoot can cause interaction between operational amplifiers unless it is held to a negligible value.

The amount of overshoot is directly proportional to d-c feedback through the filter and inversely proportional to the filter time-constant. If d-c gain is made less than 20 by feedback, overshoot will be excessive. If the filter is too large, the amplifier will be slow to recover from a temporary loss of supply voltages.

To assure adequate pulse rise-and-fall times, the amplifier should be laid out and wired to avoid excessive wiring capacitance. A d-c filament supply is essential for V_1. The supply voltages must be regulated to maintain about 45 volts at the output cathode. If different supply voltages are used, the d-c feedback circuit components must be altered.

Output Low-Pass Filters

A 5-rpm switch is used for sampling. Each of the two poles of this switch has 60 shorting-type contacts. Every other contact is intended to be grounded, providing 30 amplifier channels.

A filter suitable for shorting-type operation is shown in Fig. 3. The following design considerations exist: At the beginning and end of each sample, the filter input is shorted to ground momentarily. It is essential that signal pulses appear at the amplifier output only when the output coupling capacitor C_1 is connected to a filter, never when C_1 is grounded. For reliability, there should be a short period of time at the beginning and end of each pulse before C_1 is ungrounded or grounded. However, during these times, filter capacitor C_2 discharges back through the near-zero output impedance of the pulse amplifier. The effect is the same as that obtained by shorting the filter input to ground. In fact, the two phenomena may be lumped together so far as their effect upon the rectification efficiency is concerned.

A further design consideration involves internal leakage resistance between switch contacts. By the time the switch is ready for cleaning, resistance to ground at the filter input may be as low as 20 megohms. This resistance is denoted by R_1 in Fig. 3.

Values for Timing

As shown in the switch-contact timing diagram, Fig. 4, the timing parameters are:

t_1 = time for one switch revolution or cycle
t_2 = single pulse length
t_3 = total filter discharge time = $(t_6 + t_7 + 2t_8)$, in general less than t_2
E = rectification efficiency = $\dfrac{\text{d-c voltage recovered}}{\text{pulse amplitude}}$

Rectification efficiency, considering the effect of the discharge time t_3 is

$$E_1 \cong \frac{t_2}{t_2 + t_3} \qquad (3)$$

Regarding the effect of leakage resistance R_1, capacitor C_2 of Fig. 3 discharges through R_2 and R_1 for a very long time t_1 and charges through R_2 for a relatively short time t_2. Rectification efficiency, considering this parameter alone, is

$$E_2 \cong \frac{1}{\dfrac{R_2}{R_1}\dfrac{t_1}{t_2} + 1} \qquad (4)$$

Net rectification efficiency is somewhat better than the product of E_1 and E_2. Efficiencies on the order of 50 percent are usual. Since the pulse-amplifier gain is 1,500, a d-c to d-c gain of 750 is obtained from the stabilizing circuit.

To obtain sufficient filtering, a second low-pass filter section R_3C_3 (Fig. 3) has been added. When a double-section filter is used R_2C_2 must be much smaller than R_3C_3 to prevent damped oscillations when subjected to transients. Time constants of 6 milliseconds and 30 seconds for R_2C_2 and R_3C_3, respectively, have been found satisfactory.

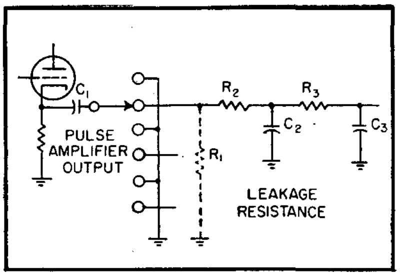

FIG. 3—Filter circuit used in output of stabilizing amplifier. Leakage resistance R_1 across contacts can be as low as 20 megohms when switch is in need of cleaning

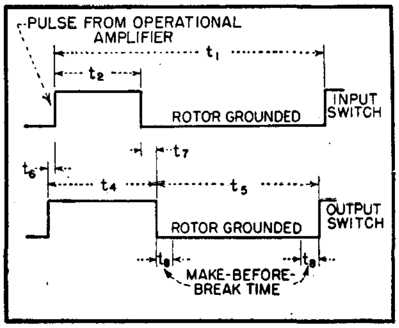

FIG. 4—Time relationships for stabilizing-amplifier input and output switch

When an operational amplifier is overloaded, the low-pass filter charges to some large voltage. When the overload is removed, several seconds are required for this filter to discharge and for the amplifier to regain its stabilized zero. This phenomena is typical of any type of stabilizing circuit using continuous balancing.

A recovery time of 20 to 30 seconds is typical.

Recovery time can be improved if clamping diodes are added at the individual filters to prevent the filter from charging under overload conditions.

An improvement factor of 5 is easily realizable.

System Performance

With any of the stabilizing-amplifier inputs grounded through a 1-megohm resistor, the d-c voltage at the corresponding output filter due to rectified noise is less than 100 millivolts. This value is equivalent to about 100 to 200 microvolts of noise at the stabilizing-amplifier input.

The following data are given for a unity-gain inverting amplifier, that is, one having equal pure resistances for Z_i and Z_f of Fig. 1. A high-quality d-c operational amplifier with regulated power supplies was employed for the tests. With no signal input, noise output is about 1 millivolt peak-to-peak. The d-c drift is not more than a few tenths of a millivolt over periods of several days. Time required for the amplifier to regain a stabilized zero after a severe and prolonged overload is 20 to 30 seconds. A recovery time of 4 or 5 seconds can be obtained if filter clamping is used.

Channel Interaction

To measure freedom from interaction under normal conditions, signals of a varying character were fed into a gain-of-ten summing amplifier (Z_i = 100,000 ohms; Z_f = 1 megohm) with amplitudes equal at least to its maximum signal-handling capability. Another gain-of-ten summing amplifier was stabilized on an adjacent channel. Signal voltage at the output of this amplifier due to interaction did not exceed 2 millivolts. When amplifier gain was reduced to unity, interaction was negligible.

Some interaction does exist under overload conditions. When the summing junction of the first amplifier reaches 30 volts, the output of the adjacent amplifier may become offset as much as 30 millivolts. This is due to an energy transfer at the input sampling switch. It is apparently a result of dielectric absorption, not resistive leakage. This phenomenon occurs even with high-quality insulating materials because of the enormous difference between signal levels at the adjacent contacts. Some improvement could perhaps be obtained by locating a grounded guard ring around each contact.

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(3) W. E. Ingerson, Drift Compensation in D-C Amplifiers for Analog Computers, paper presented at IRE National Convention, New York, 1951.