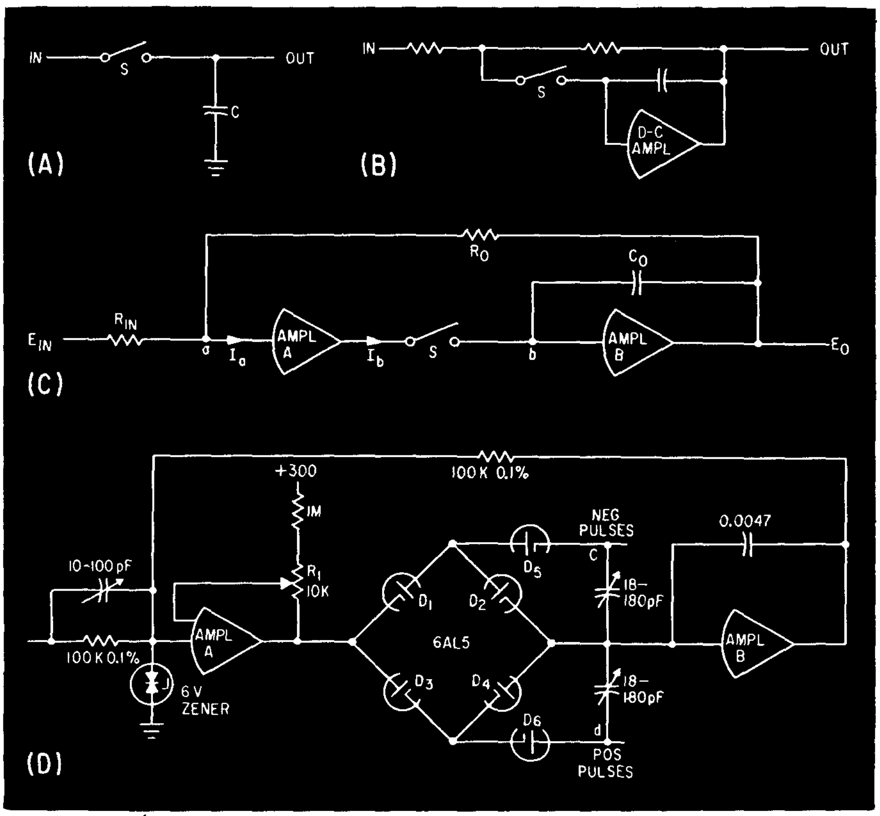

FIG. 1 — Elementary capacitor memory (A); sample-hold circuit using high-gain d-c amplifier (B); basic high-frequency sample-hold circuit (C); complete sample-hold circuit using diode-bridge as switching circuit (D)

Precision Analog Memory Has Extended Frequency Response

Used in analog circuits, the device has a dynamic range of ±50 volts, holds within 0.02 volt for 100 milliseconds, and can track a 30-volt-peak sine wave with less than 2 degree phase shift at 20 Kc

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THE STORAGE UNITS most often used in analog sample-hold circuits are capacitors that are switched in and out of the circuit to remember the capacitor voltage at the instant of switching (Fig. 1A). An analog-computer integrator in hold operation can replace a capacitor if the circuit is to drive a load (Fig. 1B). In low-frequency applications, mechanical relays may be used in the circuit of Fig. 1B, but audio-frequency applications require electronic switches, and these have the drawback that they tend to cause leakage into the holding capacitor when the switch is open.

The circuit to be described uses a relatively large holding capacitor to overcome leakage. The problem of driving the capacitor at high frequencies is solved with a d-c follower used as a current amplifier to supply current to the capacitor. The resulting circuit combines satisfactory holding ability with extended frequency response.

The analog memory circuit is used in random-process studies in conjunction with a fast repetitive computer. The amplifiers, which are on printed-circuit cards, are plugged into a module containing two sample-hold circuits together with their switching electronics and an electronic comparator circuit. This module, which uses plug-in holding capacitors, is intended mainly for a new repetitive computer[1] permitting measurement of ensemble statistics. It is also useful for various instrumentation applications, notably amplitude-distribution analyzers,[2] where voltages must be held for 50 to 100 msec, and where the storage circuit must track signal components at frequencies as high as 20 Kc. Similar units serve as repetitive integrators.

The memory circuit is also useful in connection with slow electronic

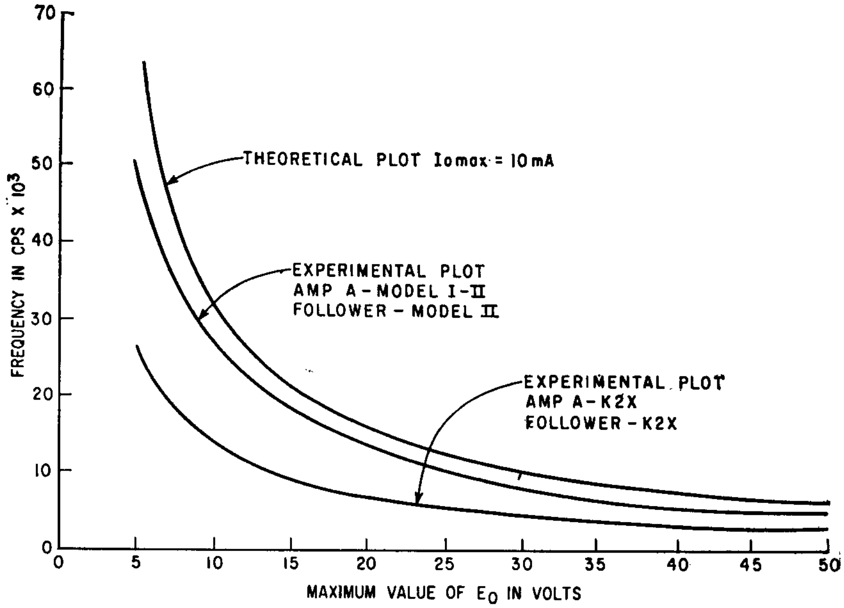

FIG. 2—Comparison between theoretical response and the actual response using various amplifier and follower types

analog computers incorporating analog storage and repetitive subroutines[3]. Finally, if shorter holding times are required (as in multiplexing applications), a smaller holding capacitor can be used without loss of accuracy, improving the frequency response.

The basic sample-hold circuit is shown in Fig. 1C. If switch S is closed and the gain of the second amplifier is very high, point b will be at approximately zero volts. Thus, if the first amplifier is a true follower, point a will be at zero volts also.

Writing the node equation at point a gives

$$E_{in}(s)/R_{in} + E_o(S)/R_o = I_a(S) \qquad (1)$$

The node equation at point b is

$$E_o(s)/(1/SC) + I_b(s) = 0 \qquad (2)$$

If the current gain of amplifier A is $A(S)$ then

$$I_b(s) = I_a(s) \times A(s) \qquad (3)$$

Substituting Eq. 3 into Eq. 2 gives

$$E_o(s)\,SC + I_a(s)\,A(s) = 0 \qquad (4)$$

Solving for I_a (s) in Eq. 4 and substituting into Eq. 1 yields the gain

$$E_o(s)/E_{in}(s) = -R_o/R_{in} \times 1/[R_oC_o\,s/A(s) + 1] \qquad (5)$$

Thus, the effect of the current amplifier is to extend the frequency response by a value equal to the current gain of the amplifier.

The complete sample-hold circuit is shown in Fig. 1D. Input and feedback resistors are 100,000 ohms and give a gain of unity at d-c. The holding capacitor of 0.0047 μf compromises between frequency response and capacitor-charging-through-leakage during the holding period. Note that addition of integrator-input resistors at the summing point of amplifier B would yield a complete repetitive-computer integrator.

Amplifier A used as a follower, is a University of Arizona Model II operational amplifier[4] which can deliver a maximum current of 10 ma. Taking the input (grid) current, I_a, as approximately 10^{-4} amps, the maximum current gain of the follower is about 10^7.

Amplifier B is the chopper-stabilized University of Arizona Model III operational amplifier,[4] which can deliver $\pm$ 100 volts at 10 ma. The follower amplifier was not stabilized, since its long-term drift (15-20 mv) is comparable to that of the electronic switch itself and does not affect the output in *hold*. Any initial offset is balanced by potentiometer R_1 at the output of the follower. It was found after warmup that the total output drift is less than 0.02 volts.

For a sine-wave input E_o sin ωt, the output with the switch closed is $-E_o$ sin ωt. The change in voltage across the capacitor is given by $dv/dt = i/c = -E_o\,\omega \cos \omega t$. The current is therefore a maximum when $\cos \omega t = 1$ and $i_{max} = -E_o c\omega$, giving an equation for the frequency at which the sample-hold circuit will overload. Figure 2 shows experimental and calculated voltages E_o as a function of frequency. Figure 2 also shows an experimental curve using Philbrick K2-X operational amplifiers as the follower and the main amplifier for purposes of comparison.

A six-diode bridge (Fig. 1D) in-

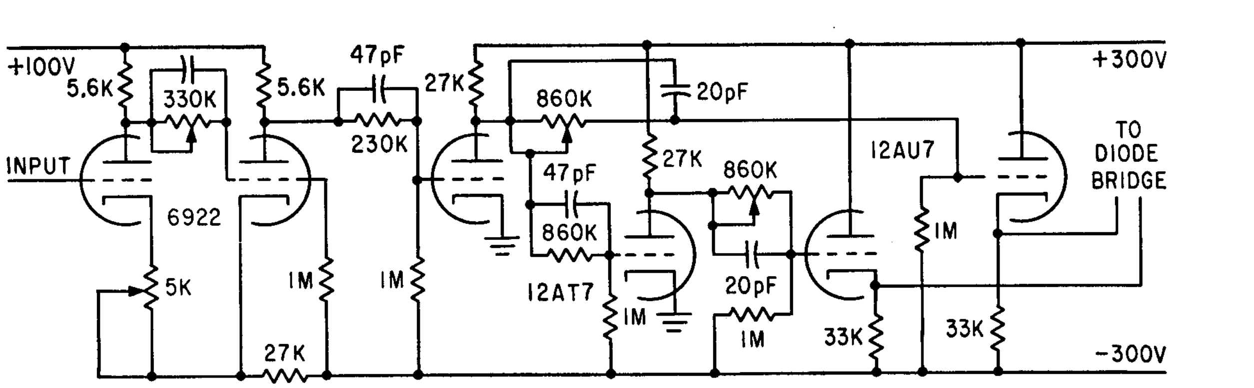

FIG. 3—Push-pull pulse amplifier for driving the diode bridge circuit. First stage of the pulse amplifier is a Schmitt trigger, whose input comes from an operational amplifier of gain 50

corporating 6AL5 diodes is used as the switch for the circuit. This type of circuit has a very high transfer impedance when off and is easily turned on and off with large or small push-pull pulses. When point *c* is positive and point *d* negative, diodes D_5 and D_6 are off and the bridge is on. Small offsets owing to differences in circuit resistance can be nulled, with the potentiometer at the follower output. When point *c* goes negative and *d* positive, diodes D_1, D_2, D_3, and D_4 are turned off. However, there is a small amount of leakage through the diodes, and differences between diode characteristics produce a small current that flows into or out of the holding capacitor and cause a small charging or discharging effect. It was found that ± 10 volt and ± 100 volt gate pulses gave the same leakage-current difference. Errors due to this leakage current in the vacuum-type diodes are small compared to the effects of capacitor dissipation and finite amplifier gain. The small variable capacitors from points *c* and *d* to the summing point balance the rise and fall time of the push-pull gate pulses. When the input pulses are balanced, the change in voltage due to switching action is less than 5 mv. Stock 6AL5 diodes were used in the bridge, and there was no attempt to match them. The resulting output drift was less than 0.02 percent of 100 volts for a holding time of 100 msec.

The ± 50-v push-pull pulses for turning the diode bridge on and off are obtained from the circuit shown in Fig. 3. The Schmitt trigger circuit acts as a comparator about zero volts and provides the input to two pulse amplifiers. Resistive networks combine the outputs of the two amplifiers with suitable bias voltages to provide the proper voltage levels, and the cathode followers furnish the push-pull output at the low impedance necessary to drive the diode bridge. Use of the Schmitt trigger permits two sample-hold circuits to be run as a memory pair in modern multipurpose analog computers (one sample-hold tracks, while the other holds)[3]. In this application, the Schmitt trigger is driven by an operational amplifier limited at ± 50 volts, with gain 50. The combination of the amplifier

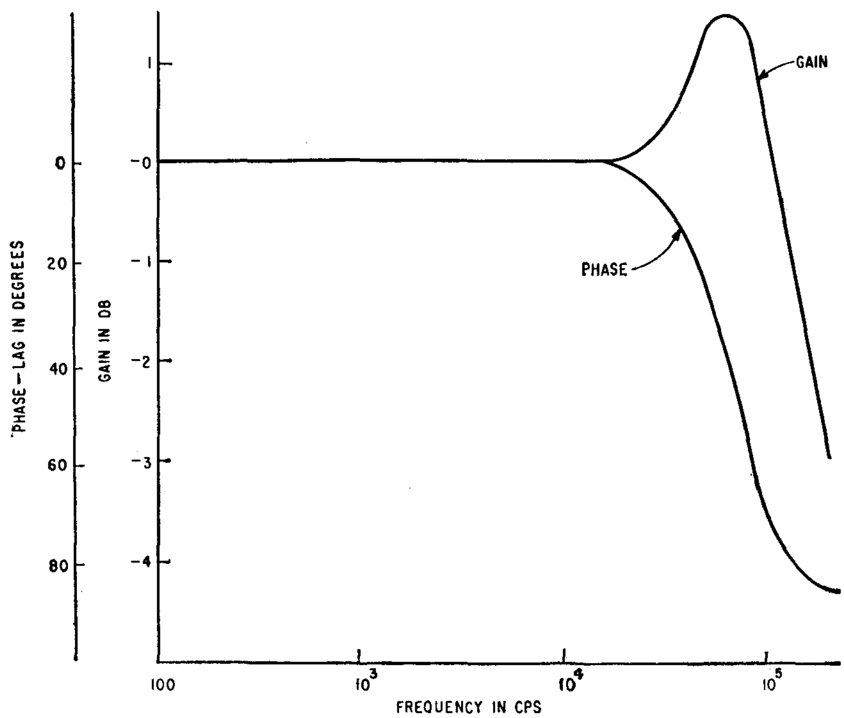

FIG. 4—Characteristics of phase and gain versus frequency, for the University of Arizona amplifier and follower

and Schmitt trigger forms a fast comparator. Note that the hysteresis and trigger level drift of the Schmitt trigger are effectively divided by the gain of the amplifier. If triggering about some d-c level is desired it is only necessary to add the d-c term at the comparator input.

If solid-state pulse circuits are used to drive the bridge, a low-voltage back-to-back Zener diode can be placed from the follower input to ground. This gives limiting-action when the switch is off and it is then possible to control the diode bridge with small push-pull pulses, such as those obtained from transistor logic modules, even though voltages as large as 50v are tracked and held.

The analog-storage circuit has a dynamic range of ± 100 volts d-c, with a static accuracy better than 0.1 percent essentially determined by the accuracy of the resistances R_{in} and R_o. The output is held within ± 20 mv for 100 msec with the switch off. Figure 2 shows the overload voltage as a function of frequency, and Fig. 4 shows the frequency response in the tracking mode. The recovery time after sampling is less than 100 μsec for ± 50 volt steps. This recovery time limits the maximum sampling rate to 10,000 samples per second with the 0.0047 μF holding capacitor shown. The plug-in holding capacitor can be changed to trade frequency response for holding time, or vice versa.

Since the University of Arizona Mod. II and III plug-in amplifiers (which were especially designed for fast analog computers) are not generally available, the circuit was also built using Philbrick K2-X amplifiers. The only result of the amplifier substitution is a reduction of the dynamic range at high frequencies, as indicated in Fig. 2.

The circuit was developed in the course of a repetitive analog computer project directed by G. A. Korn. Acknowledgment is due the Electrical Engineering Department of the University of Arizona and P. E. Russell.

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