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Pulse and Digital Circuits

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the common terminal, and let e_{xy} be the input, e_{zy} be the output, and let the gain $A' = e_{zy}/e_{xy}$. Then

$$A' = \frac{e_{zy}}{e_{xy}} = \frac{-e_{yz}}{e_{xz} + e_{zy}} = \frac{-e_{yz}}{e_{xz} - e_{yz}} = \frac{-e_{yz}/e_{xz}}{1 - e_{yz}/e_{xz}} = \frac{-A}{1-A}$$

If $A = -\infty$, $A' = +1$, as anticipated.

The effect of a finite value of A on the linearity of a Miller sweep is now to be investigated. In accordance with the principle of the virtual

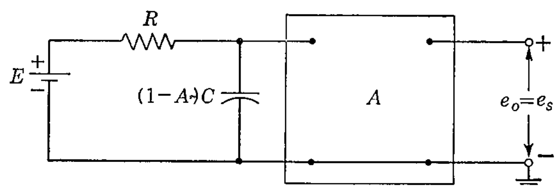

FIG. 7-16. The equivalent circuit of the Miller integrator for finite gain A.

ground explained in Sec. 1-12 the equivalent circuit is as drawn in Fig. 7-16. The output or sweep voltage is given by

$$\begin{aligned} e_s &= AE(1 - \epsilon^{-t/RC(1-A)}) \\ &\cong E\frac{A}{1-A}\frac{t}{RC}\left[1 - \frac{t}{2RC(1-A)} + \cdots\right] \\ &\cong -\frac{Et}{RC}\left(1 - \frac{t}{2RC|A|} + \cdots\right) \end{aligned} \qquad (7\text{-}7)$$

since A is large and negative. Comparison of Eq. (7-7) with Eq. (7-4) shows that, for a fixed sweep amplitude E_s relative to the supply voltage E [see Eq. (7-5)], the deviation from linearity of the Miller sweep is $1/|A|$ times that of the uncompensated time base.

The effect of a deviation of A from 1 for the bootstrap sweep is now to be investigated. Referring to Fig. 7-14*b*, we have

$$E = iR + e_i - e_o = iR + e_i(1 - A) \qquad (7\text{-}8)$$

because $e_o = Ae_i$. Dividing by $1 - A$, gives

$$\frac{E}{1-A} = i\frac{R}{1-A} + e_i \qquad (7\text{-}9)$$

Remembering that e_i is the voltage across capacitor C, Eq. (7-9) leads to the equivalent circuit of Fig. 7-17. The output or sweep voltage is given by

$$\begin{aligned} e_s &= \frac{AE}{1-A}\left(1 - \epsilon^{-\frac{t(1-A)}{RC}}\right) \\ &\cong AE\frac{t}{RC}\left[1 - \frac{t(1-A)}{2RC} + \cdots\right] \end{aligned} \qquad (7\text{-}10)$$

Since A is close to unity, we see, by comparing Eq. (7-10) with Eq. (7-4), that the deviation from linearity of the bootstrap circuit is $(1 - A)$ times that of the uncompensated time base. It follows from this dis-

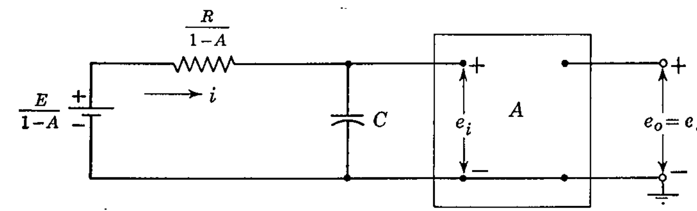

FIG. 7-17. The equivalent circuit of the bootstrap sweep.

cussion that a Miller amplifier (of gain A_M) will give the same amplitude, sweep speed, and deviation from linearity as a bootstrap amplifier (of gain A_B), provided that $|A_M| = 1/(1 - A_B)$. For example, a bootstrap circuit with a gain of 0.95 is equivalent to a Miller circuit with a gain of 20. The decision between these two circuits is often difficult to make. Some practical considerations are given in the following sections. Other fine points are brought out in Chap. 16 in connection with the use of these sweep circuits for precision time modulation.

7-5. The Miller Sweep.[2] A simple Miller sweep is shown in Fig. 7-18*a*. The negative bias should not be so large that the tube is cut off. Observe that E_{bb} is used both to charge C and to supply tube current. When S opens, a negative-going sweep will appear at the plate. However, as indicated in Fig. 7-18*b*, the sweep will be preceded by a positive jump. The jump results from the finite output impedance of the amplifier which has heretofore been neglected (see Prob. 7-13). This jump can be eliminated by the addition of a resistor $r = 1/g_m$ in series with the capacitor C (see Prob. 7-14).

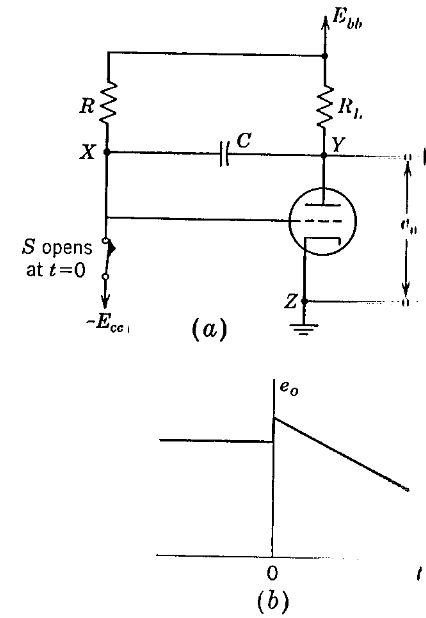

FIG. 7-18. A Miller sweep with the gate applied to the grid. (*a*) Circuit; (*b*) output waveform.

A Miller sweep with symmetrical outputs is indicated in Fig. 7-19. The triode T_1 with its grid clamped to ground acts as the closed switch S

of Fig. 7-18. A negative gate applied to the grid cuts T_1 off and allows C to charge from E_{bb} through R and the Miller tube T_2. The output e_{o1} from the plate of T_2 is a negative-going sweep. This voltage is applied to the grid of T_3 through the resistor R_2 and an equal resistor R_2 is used for feedback from plate to grid of T_3. Hence, T_3 acts as an operational phase inverter (see Sec. 1-13) and the output e_{o2} is a positive-going sweep. The symmetrical voltages e_{o1} and e_{o2} drive the CRT horizontal plates. It should be noted that the negative bias of Fig. 7-18 has been replaced by the voltage across the cathode resistor R_k. This resistor does *not* introduce degeneration because the current through it remains constant. Thus, as the current in T_2 increases, the symmetrical current in T_3

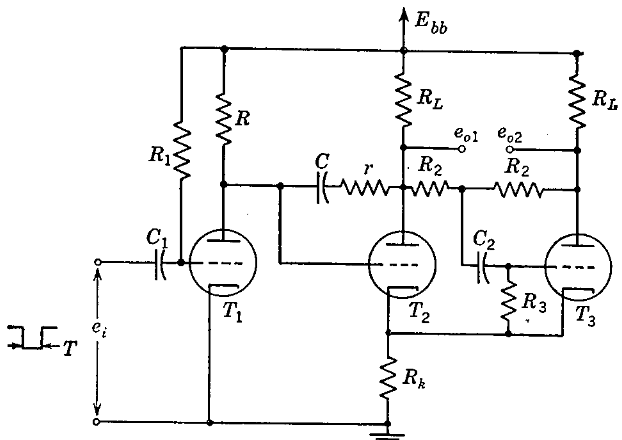

FIG. 7-19. A symmetrical Miller sweep. The switch tube is T_1, the Miller integrator is T_2, and the operational inverter is T_3.

decreases by the same amount, leaving the current in R_k unchanged. The grid leak for T_3 is R_3 and the blocking capacitor C_2 keeps the high plate voltage of T_2 from reaching the grid of T_3. The time constant R_3C_2 must be large enough to introduce negligible transmission error (see Sec. 7-1).

A total sweep voltage equal to the supply voltage can be obtained by choosing $e_{o1} = -E_{bb}/2$ and hence $e_{o2} = +E_{bb}/2$. From the theory developed in Sec. 7-4 the displacement error under this condition is $\epsilon_d \cong \frac{1}{8}\frac{E_s}{E_{bb}}\frac{100}{|A|} = \frac{100}{16|A|}$ per cent. It is not difficult to obtain a gain $|A|$ of 15 with a triode (say, a 12AU7 tube), and then $\epsilon_d \cong 0.4$ per cent for a total swing of E_{bb} volts. The sweep speed is E_{bb}/RC volts/sec.

At the end of the sweep time the capacitor C must discharge and return to its quiescent voltage. The discharge path is through the amplifier output impedance and through a switching tube such as T_1 in Fig.

7-19. If fast retrace time is important, then C should be kept as small as possible and R chosen sufficiently large to give the desired sweep speed. For practical reasons it is advisable not to permit R to exceed several megohms. A high-current switching tube and, additionally, the use of a cathode follower interposed between the capacitor C and the amplifier output will reduce the recovery time still further. The recovery may also be hastened by selecting the time constant R_1C_1 (Fig. 7-19) to be comparable to the width of the gating signal, since under these circumstances there will be a pronounced overshoot at the grid at the termination of the gate. A Miller sweep using a cathode follower to speed recovery and using a pentode amplifier for higher gain is shown in Fig. 7-20. Note that the low output impedance of the cathode follower makes the resistor r in series with C (Fig. 7-19) unnecessary.

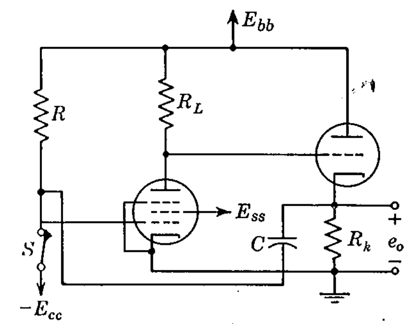

FIG. 7-20. A Miller sweep using a cathode follower in order to reduce the retrace time. Note that a negative-going sweep is obtained at the low impedance output of the cathode follower.

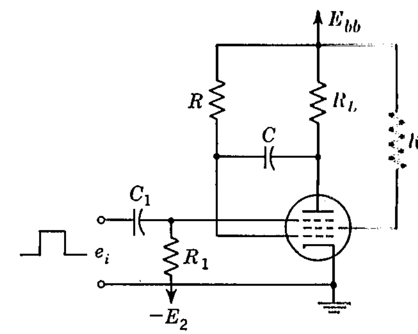

FIG. 7-21. A suppressor-gated Miller time-base generator.

7-6. Pentode Miller Sweep with Suppressor Gating. If a pentode is used as the amplifier tube of a Miller sweep, then the gating voltage may be applied to the suppressor grid instead of to the control grid. A suppressor-gated Miller integrator is indicated in Fig. 7-21. A tube with a sharp cutoff suppressor characteristic is used, such as the types 6AS6, 7AK7, 5915 (RCA), 6CS6 (Raytheon), and 6BH6 (Tungsol). The 6SA7 converter tube[3] has also been used in this application. Initially the suppressor grid is biased to plate current cutoff, while the control grid is clamped to the cathode. All the cathode current flows to the screen and hence the screen voltage is low. The waveforms at all the electrodes are given in Fig. 7-22. A positive gate applied to the suppressor drives this electrode either slightly positive or to clamp. Clamping may occur either because the impedance of the driving source is large in comparison with the suppressor-cathode resistance or because a diode is added to the circuit from suppressor to ground. This increased suppressor voltage permits plate current to flow and the plate voltage drops. Since the voltage across the Miller capacitor C cannot change instantaneously, the grid voltage must drop by the same amount E_1 that the plate falls. The grid voltage is now $-E_1$, the tube finds itself operating above cutoff, and a negative-going sweep forms at the plate. The load resistor R_L is large so that bottoming will take place (see Sec. 4-3). The load line is drawn on the plate characteristics in Fig. 7-23. Since $-E_1$ is very close to the cutoff bias, we have considered that the tube characteristic corresponding to the grid voltage $-E_1$ is coincident with the abscissa.

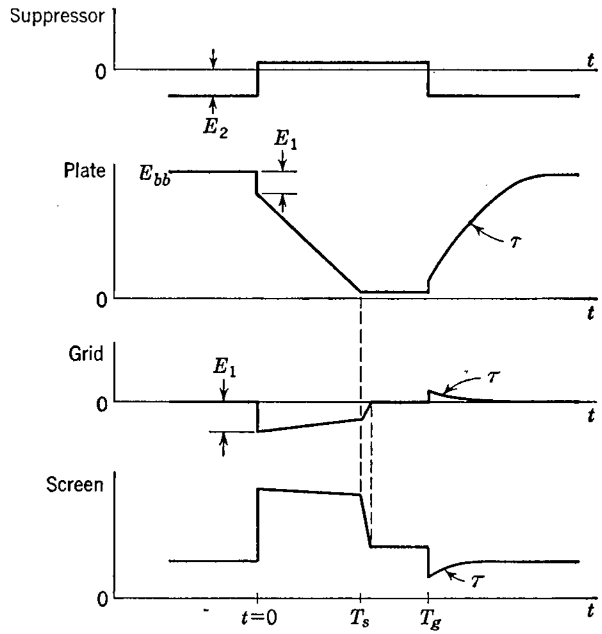

FIG. 7-22. The waveforms for a suppressor-gated Miller sweep generator.

For a type 6AS6 tube, the order of magnitude of E_1 is 5 volts and bottoming begins when the grid has increased by only one or two volts. For example, if $E_{bb} = 300$ and the amplifier gain is 150, then the grid will increase by $300/150 = 2$ volts for complete "run-down."

When the grid voltage drops from zero to $-E_1$, the cathode current falls, the screen current drops, and hence the screen voltage rises as indicated in Fig. 7-22. During the formation of the sweep the grid rises slightly, as noted above, and the increased screen current results in a slight decrease in screen voltage. When the plate voltage bottoms, the grid voltage increases to zero with a time constant RC, the space current and hence screen current increases, and the screen voltage drops, as indicated in Fig. 7-22. The screen voltage does not quite fall to its value for $t < 0$

because some of the cathode current is now being collected by the plate, whereas for $t < 0$ all the space current goes to the screen.

At the end of the gate the suppressor again cuts off the plate current. The capacitor C whose voltage has fallen almost to zero recharges toward E_{bb} through R_L and the grid-cathode resistance r_c with a time constant $\tau = (R_L + r_c)C \cong R_LC$. The grid voltage will be driven positive by approximately r_cE_{bb}/R_L volts. This positive grid voltage will increase the cathode current above its value for $t < 0$, and hence there will be a dip in screen voltage below its value for $t < 0$. The overshoot in grid voltage and undershoot in screen voltage are indicated in Fig. 7-22.

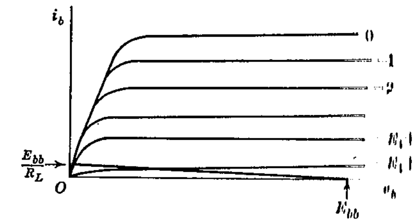

FIG. 7-23. Illustrating bottoming in a pentode and the fact that the grid voltage changes by only a few volts during the entire sweep voltage.

At $t = 0+$, the voltage across R is $E_{bb} + E_1$, and since the current through R passes through C, the initial sweep speed is $(E_{bb} + E_1)/RC$ volts/sec. As long as the amplifier gain remains high, the sweep speed remains essentially constant. Hence, a linear ramp results for almost the entire plate voltage rundown except near the very bottom.

If the gate width T_g is less than the time T_s for the capacitor to discharge completely, then there will be no bottoming and the flat portions of Fig. 7-22 between T_s and T_g are missing. The screen voltage is itself a gating voltage, and, if the sweep is being used in connection with a scope display, can be used as an intensifier to brighten the CRT trace during the sweep time and to cut off the CRT beam during the retrace time. The recovery time may be made quite small by driving the capacitor C from a cathode follower as in Fig. 7-20. Under these circumstances the recovery time constant is $\tau = (C)(R_o + r_c)$, where R_o is the output impedance of the cathode follower and r_c is the grid-cathode resistance.

The step in the plate voltage at $t = 0+$ *cannot* be eliminated by adding a resistor r in series with C in Fig. 7-21, as was done for the grid-gated Miller integrator. The use of the resistor r is effective because the amplifier of the grid-gated circuit is initially biased within its grid base. The suppressor-gated circuit, however, is held beyond cutoff in the quiescent condition. When the gate is applied, the tube must draw some plate current, and hence the plate voltage must drop somewhat.

7-7. Phantastron Circuits.[4] The screen waveform of Fig. 7-22 is a positive step for the interval of the linear rundown. Hence, it is possible to start the sweep by means of a narrow pulse or trigger and to couple the output from the screen to the suppressor so that the positive gate needed at the latter grid is supplied internally. A circuit in which a Miller time base is initiated with a trigger and the circuit then supplies its own gate is called a *phantastron.**

The screen-coupled phantastron is drawn in Fig. 7-24. This circuit differs from the suppressor-gated Miller sweep (Fig. 7-21) only in that the screen and suppressor voltages are obtained from a bleeder arrangement R_1-R_2-R_3. These resistors are so chosen that in the quiescent state the suppressor grid is sufficiently negative (say, $-E_2$) so that no plate current flows, all the space current going to the screen. Assume now that a positive trigger is applied at $t = 0$ to the suppressor so as to allow the plate to draw current. The plate voltage drops, the grid voltage drops the same amount (say, E_1), the cathode current falls, and the screen

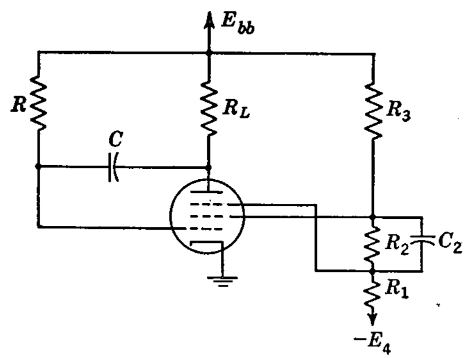

FIG. 7-24. The screen-gated phantastron.

voltage rises. This causes the suppressor voltage to rise because it is obtained from the same bleeder as the screen potential. The capacitor C_2 is a speed-up capacitor (see Sec. 5-3). The action described above is regenerative and the tube is rapidly driven from cutoff to its normally *on* condition and the Miller sweep is initiated.

The waveforms at all the electrodes are given in Fig. 7-25 and are identical with those in Fig. 7-22 except that the flat portions at the end of the run-down are missing. As soon as the tube bottoms and the plate can fall no further, the plate side of C in Fig. 7-24 remains at a fixed potential. Hence, the grid side of C must rise with respect to ground (with a time constant RC) because current continues to flow from E_{bb} through R through C into the tube plate. As the grid rises, the cathode current increases, the screen current increases, and the screen voltage drops. Because of the action of the bleeder arrangement the suppressor voltage also falls and the plate current decreases. A reduction of plate current means an increase in plate voltage which in turn causes the grid

* The British considered the operation of this circuit as *fantastic* and dignified it with the name *phantastron*.

to rise still further. This action is regenerative and the suppressor voltage is rapidly driven negative. The waveshapes for $t > T_s$ in Fig. 7-25 are explained in exactly the same manner as the waveshapes for $t > T_g$ in Fig. 7-22. There is one difference between these two figures in the region under consideration. Since the suppressor voltage comes from the same bleeder as the screen voltage, there will be an undershoot at the suppressor, as indicated in Fig. 7-25.

Triggering may also be done with negative pulses applied to the plate and hence fed to the grid through the capacitor C. A negative trigger so applied reduces the cathode current and consequently raises the screen

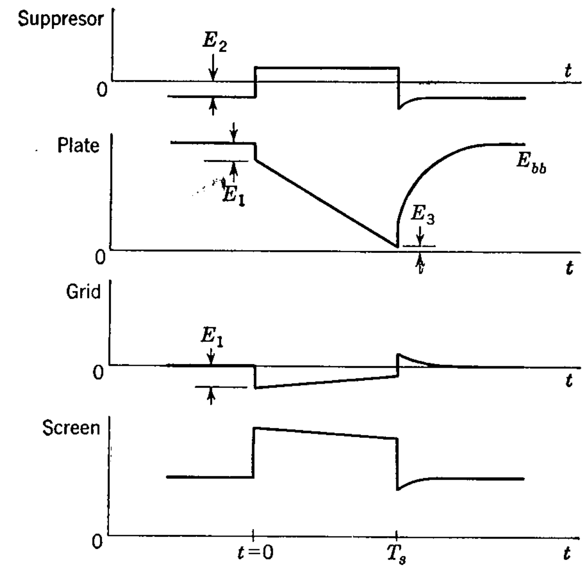

FIG. 7-25. Waveforms in the screen-coupled phantastron.

voltage. The rise of screen voltage is transmitted to the suppressor to bring the suppressor above the point of plate current cutoff. The trigger size should be large enough to start the regenerative action but not so large as to cut off the tube current. If the tube should be driven below cutoff, the grid voltage will rise initially with a time constant RC into the conducting region and there will be a delay between the application of the trigger and the start of the sweep.

The phantastron circuit has a recovery time constant $\tau = R_LC$. If a shorter retrace time is desired, then a cathode follower can be interposed between the plate of the amplifier and the capacitor C, as was done for the externally control-grid-gated Miller sweep of Fig. 7-20. Since the sweep voltage at the plate of the pentode starts near E_{bb} and since this voltage is applied directly to the grid of the cathode follower, a separate supply

E'_{bb} must be used for the cathode follower with $E'_{bb} > E_{bb}$. The magnitude of the overshoots and undershoots is greatly increased (perhaps by a factor of 10) if a cathode follower is used. The reason for this feature is that the plate of the amplifier is no longer loaded down by the low grid-cathode resistance r_c which allowed the grid to overshoot to only $r_c E_{bb}/R_L$ volts. With a cathode follower in the circuit, when the plate rises at the end of the sweep it carries the grid of the cathode follower way up with it and hence the grid of the pentode can be driven several volts positive.

The sweep speed is, as with the simple Miller integrator, $(E_{bb} + E_1)/RC$ volts/sec and can be adjusted by changing E_{bb}, R, or C. If the rundown proceeds to within E_3 volts of ground (see Fig. 7-25), then the amplitude of the sweep is $E_{bb} - E_1 - E_3$. The sweep time T_s is the amplitude divided by the speed, so that

$$\frac{T_s}{RC} = \frac{E_{bb} - E_1 - E_3}{E_{bb} + E_1} \tag{7-11}$$

If $E_{bb} \gg E_1 + E_3$, then $T_s \cong RC$, a result which is independent of variations in E_{bb}. The next approximation is obtained by dividing the numerator in Eq. (7-11) by the denominator with the result

$$x \equiv \frac{T_s}{RC} = 1 - \frac{2E_1 + E_3}{E_{bb} + E_1} \cong 1 - \frac{2E_1 + E_3}{E_{bb}} \tag{7-12}$$

Taking the derivative, we find

$$\frac{dx}{x} \cong \frac{2E_1 + E_3}{E_{bb}} \frac{dE_{bb}}{E_{bb}} \tag{7-13}$$

For example, if $E_1 = E_3 = 5$ volts and $E_{bb} = 150$ volts, then a 10 per cent change in supply voltage ($dE_{bb}/E_{bb} = 0.1$) gives

$$\frac{dx}{x} = \frac{15}{150} \times 0.1 = 0.01$$

or a 1.0 per cent change in sweep time.

A diode (T_2 in Fig. 7-26) may be used to clamp the suppressor to ground during the time when the time base is being formed. Hence the negative supply $-E_4$ plays no part in determining conditions during the interval T_s. The voltage $-E_4$ is needed only to ensure plate-current cutoff before the circuit is triggered. Variations in the negative supply have negligible effect on the sweep time T_s.

Variations in filament voltage should affect E_1 and E_3 to some extent. Experimentally it is found that a 10 per cent change in filament voltage results in only a few tenths of a per cent change in T_s and in a direction opposite to the change due to a plate supply variation. If tubes are changed, then T_s may change by a few per cent because $2E_1 + E_3$ varies from tube to tube.

Comparing Eq. (7-7) with Eq. (7-4), it follows that

$$\epsilon_d = \frac{1}{8} \frac{T_s}{RC} \frac{1}{|A|} \cong \frac{1}{8} \frac{1}{|A|} \tag{7-14}$$

If the amplifier gain is 100, then $\epsilon_d \cong 0.13$ per cent. (Incidentally, if linearities under 1 per cent are to be realized, then the capacitance C must be independent of voltage to this precision. A mica capacitor is usually satisfactory, whereas a paper capacitor may not be.) Here, then, is a circuit possessing many fine characteristics: excellent linearity of sweep and a time-base duration whose value is not very sensitive to positive, negative, or filament supply voltages and whose sweep speed

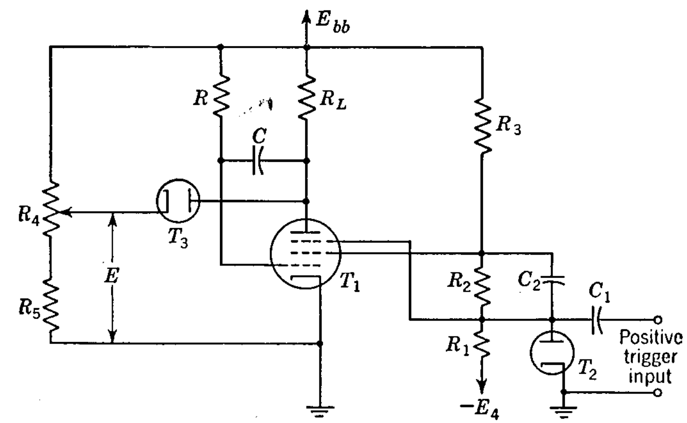

FIG. 7-26. The screen-coupled phantastron as a delay unit.

is readily adjusted. With a trigger input a square-wave output is obtained at the screen, in addition to the linear output at the plate, and hence the circuit is analogous to the plate-coupled monostable multi discussed in Chap. 6. One of the principal applications of the phantastron is as a delay unit. If the output at the screen is differentiated (peaked), then a negative output pulse is obtained, delayed T_s sec from the triggering pip. The delay is adjusted by controlling the voltage E from which the run-down begins. A plate-catching diode T_3 is ideal for this purpose and the complete circuit is shown in Fig. 7-26. The waveforms are given in Fig. 7-25 except that the plate voltage starts at E rather than E_{bb}. The overshoot at the grid is approximately $E_{bb}r_c/R_L$, where r_c is the static grid-cathode resistance and is independent of E and therefore T_s. This characteristic is different from the corresponding one for the plate-coupled multivibrator where the overshoot increases with delay. The delay T_s is a linear function of E except for small delays where curvature due to bottoming becomes important. Incidentally, T_3 also serves the useful purpose of reducing the recovery time because it catches the plate which is rising toward E_{bb} when it reaches E (see Fig. 7-28).

Analogous to the cathode-coupled monostable multi a cathode-coupled monostable phantastron can be constructed as indicated in Fig. 7-27. In the quiescent state the suppressor potential (the voltage E_2 across R_1) is much lower than the cathode voltage so that the plate current in T_1 is zero. The grid is clamped to the cathode and the plate is clamped to the control voltage E. A positive trigger of large enough magnitude is applied to the suppressor so that plate current commences to flow. This current causes the plate to fall, and because of the capacitive coupling the grid falls an equal amount. This drop in grid voltage decreases the

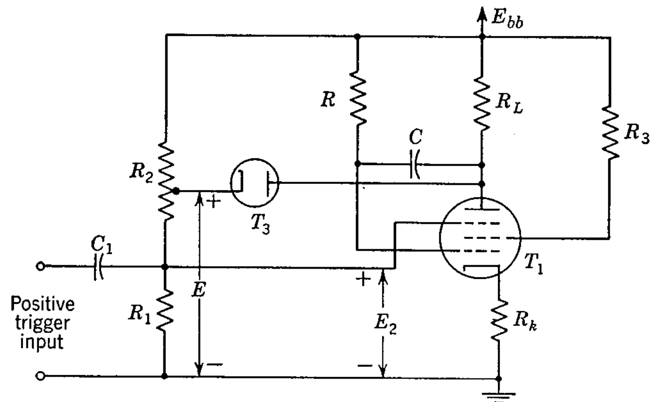

FIG. 7-27. The cathode-coupled phantastron as a delay circuit.

cathode current and the cathode potential falls. Hence, the suppressor voltage increases relative to the cathode and more plate current is drawn, etc. This explanation shows that the circuit is regenerative, and at $t = 0+$ normal plate current flows and the Miller run-down commences.

The waveforms are indicated in Fig. 7-28. Because of cathode-follower action the grid and cathode waveforms are almost identical. Since the grid follows the cathode drop at $t = 0+$, the plate, which is tied to the grid through C, must drop the same amount. Hence, the initial fall in plate potential E_1 may be larger by a factor of about 10 than the corresponding drop in the screen-coupled phantastron. The overshoots at the grid and cathode and the undershoot at the screen can be minimized by using a grid-catching diode connected with its plate at the grid of T_1 and its cathode at a tap on R_2 such that the voltage at this point is 1 or 2 volts less than the quiescent cathode potential. The exponential voltage at the plate during the retrace time ends abruptly at E because of the plate-catching diode. This abrupt termination of the plate waveform is reflected in the other waveforms in Fig. 7-28, as indicated. The

vertical sides in Fig. 7-28 are actually of the order of 1 μsec in duration. These waveforms should be compared with the analogous ones in Fig. 6-11 for the cathode-coupled monostable multi.

The cathode-coupled phantastron has the following advantages over the screen-coupled circuit. No negative supply is needed. The screen is a free (unloaded) electrode from which a positive gate is obtained. A negative gate is available at the cathode. The principal disadvantages

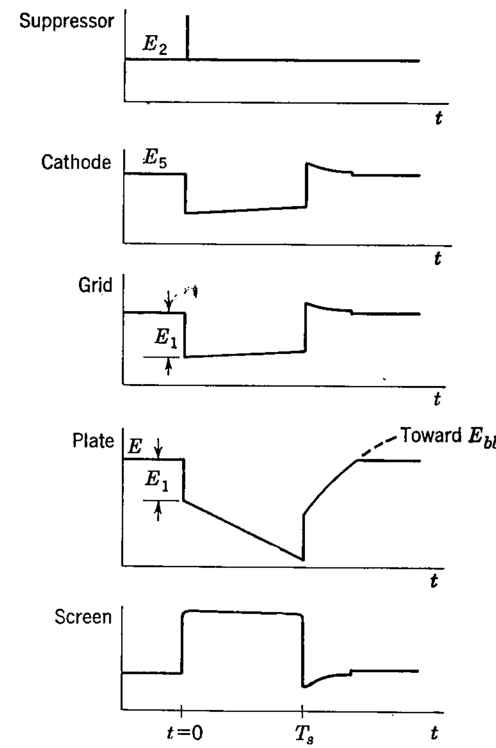

FIG. 7-28. Waveforms in the cathode-coupled phantastron.

are that there is a larger initial step in plate voltage and the gain of the amplifier is smaller because of the cathode degeneration introduced by R_k. This decreased gain means that the linearity is somewhat poorer.

The phantastron has the advantage over the cathode-coupled multi in that the former is much less sensitive to tube characteristics and to supply-voltage variations than the latter. For example, if the E_{bb} supply changes by 10 per cent in a multi circuit, we may expect the delay to change by perhaps 5 per cent, which is five or ten times what can be expected in the phantastron circuit. Also, the phantastron delay can be made more linear than that of the multi if sufficient gain is used. An astable phantastron circuit is suggested in Prob. 7-16.

The phantastron circuit is limited to the generation of linear sweeps of duration of the order of 10 μsec or longer because of the effect of the stray capacitance to ground at the various tube electrodes. Williams

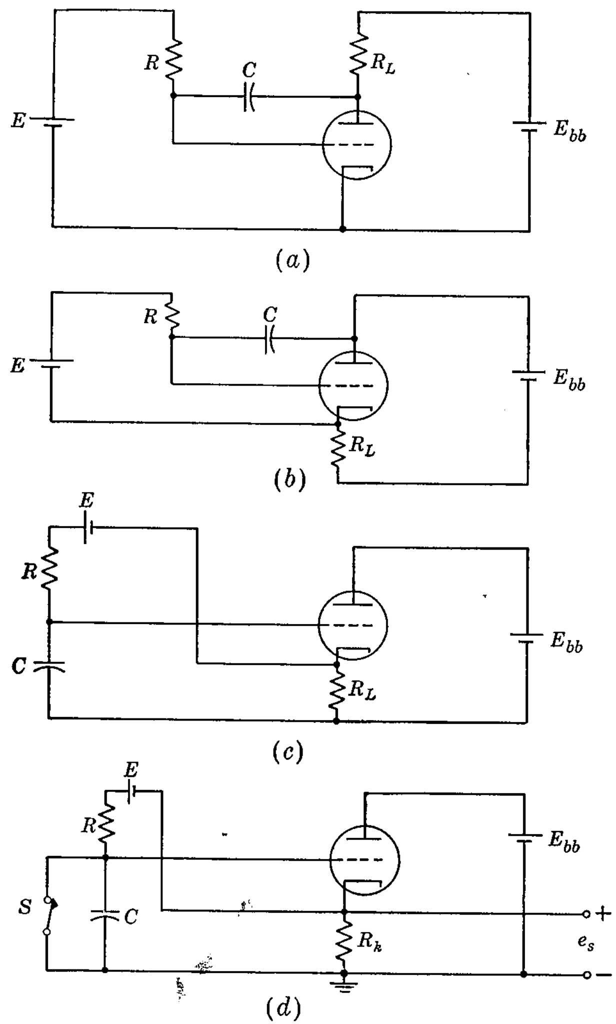

FIG. 7-29. Illustrating that a Miller integrator and a bootstrap sweep are different forms of the same circuit.

and Moody[3] describe circuits of the Miller type, called *sanatron* or *sanaphant,* which are capable of giving precise delays as short as 1 μsec. These circuits are essentially phantastrons in which a separate tube is used to generate the necessary gate from the input trigger.

7-8. The Bootstrap Sweep. In Fig. 7-29*a* the Miller sweep of Fig. 7-18 has been redrawn. The switch S has been omitted, no ground connection

is indicated, and the tube supply voltage has been separated from the capacitor-charging voltage. Figure 7-29*b* is equivalent to Fig. 7-29*a*. In Fig. 7-29*c* one terminal of C has been moved from one side of E_{bb} to the other. This change will have no effect on signal voltages. In Fig. 7-29*d* one point has been grounded, output terminals have been selected, and R_L has been relabeled R_k. The switch S which clamps the circuit at some initial level until opened is located in different positions in this last circuit and in Fig. 7-18. Because of this new switch location

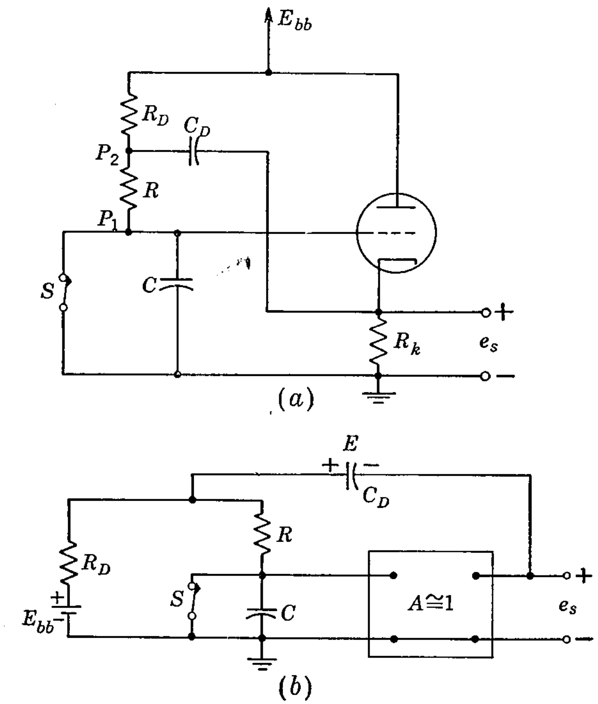

FIG. 7-30. (*a*) A practical form of the bootstrap sweep; (*b*) the equivalent circuit.

there will be no jump in the output voltage when S is opened. The circuit of Fig. 7-29*d* has the form given in Fig. 7-14*b* for the *bootstrap* sweep. The above discussion illustrates once more that the Miller integrator and the bootstrap sweep are two forms of the same circuit. The sweep voltage may be calculated from Eq. (7-10).

The practical disadvantage in Fig. 7-29 is that neither side of the supply E is grounded. This disadvantage may be remedied essentially by replacing E by a charged capacitor C_D, as shown in Fig. 7-30. It is necessary that C_D be large enough so that the voltage across C_D does not change appreciably during the sweep time. If the voltage across C_D were truly constant and if the cathode follower had exactly unity gain, then point P_2 in Fig. 7-30 would exactly follow point P_1. Hence, the