

A PULSE GENERATOR FOR SWEEP CALIBRATION

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INTRODUCTION

This research project for a thesis was selected after conferring with Mr. Wm. R. Ford, under whom the research work was done. It was decided that the construction of a pulse generator to perform certain desired functions would be both challenging to the author and beneficial to the television laboratory as a piece of additional test equipment.

PROBLEM

Before actual construction was begun on the pulse generator, the various desired functions had to be decided upon in order that the circuits to be used in the generator could be selected and evaluated. These desired functions are as follows.

(1) The pulses had to be variable in their recurrence time. The time interval between pulses should be selectable by a multi-tap switch controllable from the panel. These intervals were: 0.5, 10, and 100 microseconds, corresponding to pulse frequencies of 2 megacycles, 100 kilocycles, and 10 kilocycles per second, respectively.

(2) In order to obtain high accuracy and resolution with these pulses, the pulse deviation had to be extremely short. A pulse duration as large as 5 per cent of the pulse interval seemed admissible. Of course, it was hoped that shorter durations would be realized.

(3) Since this pulse generator would only find application when allied with other equipment, it was decided that a pulse

output variable from 0 to 50 volts would be necessary, for in all cases the higher the pulse-voltage swing, the more accurate the wave form, because all ripple and noise voltages plus many of the transient responses would be suppressed to minor variations about the neutral axis.

(4) In allying this pulse generator with other equipment, both positive and negative pulses should be available in order that simple direct connection could be made to equipment without the need of inverting networks.

(5) Again, to facilitate the use of this pulse generator with other equipment, it was mandatory that the output impedance of the generator be relatively low. This low-impedance output would insure an unchanged pulse-wave shape when supplied to a variety of different input impedances. Also, with low Z output, the shunt capacity effects on the leads are lessened and spurious signal pick-up is decreased.

(6) Insuring accurate pulse intervals is of prime importance as these pulses will be required to give precise markers and triggers. The circuits used to generate these pulses would have to be capable of high stability both in electrical and mechanical construction so that only occasional and random checks against a frequency standard would be sufficient. Simplicity in design would be required, so those adjustments necessary for accurate operation would be neither complex nor tedious.

(7) In many of the proposed applications for this pulse generator, the pulses will be combined with various other wave forms supplied from different sources. In comparing these pulses with

other wave forms, both the pulses and wave forms must be in proper phase, requiring that a phase shifter be incorporated in the generator so the pulses can be moved along the time base to coincide with the wave form under comparison.

(8) Assuming that these pulses would be used to monitor the various wave forms from a television synchronous generator, the pulses would have to be initiated at a desired point on the signal wave in order that close comparisons could be made. It is likely the initiating or triggering would be done by the horizontal sync pulses from the sync generator. But the trigger pulse might not be limited to that stated above, so the triggered circuit must be responsive to many pulse forms that may vary in duration, rise time, peak voltage, and other possible transient wave shapes. In fact, such voltage variations as 0.1 to 1000 volts peak and wave shape variations from a square wave to a sharp spiked output from a Gieger-Mueller tube could be expected.

(9) Not only should the triggered circuit be responsive to the above mentioned variations, but also it should be capable of responding either to positive or negative trigger pulses, for it cannot be assumed that all the associated equipment to be used with the pulse generator will supply the same polarity trigger.

APPLICATIONS

From the beginning, it was decided that this pulse generator would be designed and constructed to be completely compatible with the Browning oscillosynchroscope now finding wide use in the television laboratory. The Browning is being used primarily

to view wave forms originating in the television synchronizing generator.

By viewing the synchronizing generator's wave forms versus the triggered sweep incorporated in the Browning, it is possible to measure the duration and rise time of the generated pulses. The triggered sweeps have to be extremely accurate and stable since the synchronous generator is adjusted for correct output wave forms as they appear on the screen of the scope. These wave forms must comply with the rigid standards specified by the Federal Communications Commission. The pulse generator now under consideration would supply precisely-spaced marker pulses to be viewed versus the Browning's triggered sweep, and so establish markers to calibrate the triggered sweep.

These pulses when impressed on the Z-axis (intensity) of the Browning, will place intensity markers on the actual wave form under inspection. If the marker pulses are used for intensity modulation on the Z-axis, short duration and 50-volt amplitude pulses are needed in order to give good definition. Both positive and negative pulses are required for either increasing or decreasing the intensity of the beam. Triggered sweeps of .25, .5, 1.5, 20, and 200 microseconds per inch are provided within the Browning.

When impressing the marker pulses from the pulse generator on the triggered sweep, it is important that these markers are initiated simultaneously with the sweep so the pulse generator is triggered by the same pulse that triggers the Browning's sweep. The triggering pulses for the triggered sweep may come from the internal trigger supply of the Browning, or, which is more likely,

from some external supply. Since this external trigger might be the horizontal synchronizing pulses from the television sync generator or possibly another pulse generator, this pulse generator now under consideration must be capable of accepting wide variations in amplitude, duration, and frequency of the triggering pulse. To show the compatibility of this pulse generator to the Browning oscillosynchroscope, a block diagram of a typical equipment set-up is presented in Plate I, Fig. 1.

This pulse generator could be used to calibrate radar oscilloscope sweeps by checking the time delay between transmitted and received pulses. Also the radar range marker's accuracy might be verified with this pulse generator.

This pulse generator would also find usage as a frequency standard in pulse-time communications. Here the generator would determine the pulse spacing at the final stage of the transmitter or in the monitor receiver receiving the transmitted signal.

Many additional applications are undoubtedly possible. These would be limited only by the ingenuity of the operator and the facilities present in the laboratory.

CIRCUITS

It has been shown what the desired functions of the pulse generator are and what some possible applications are of a generator possessing these functions. Now the task at hand was to devise and construct a pulse generator that will meet the proposed conditions. By referring to the many texts available, a number of circuits that might possibly work in this application were found. Each circuit has its own idiosyncrasies and limitations,

so only by a close analysis were the applicable circuits ferreted out from those undesirable. This section will present those circuits initially selected and now their number was reduced to the final combination that would give the desired functions. First the circuits for pulse generator would be designed, then the control circuits would be added. In the following sections each circuit is analyzed and commented upon.

Clipped Sine Waves, First Attempt

Plate I, Fig. 2, shows the block diagram of one method for obtaining pulses from a clipped sine wave.

Sine-wave oscillator. The oscillator was of the electron-coupled type with frequency control effected by a crystal. Its schematic is shown in Plate II, Fig. 1.

This circuit is an amplifier operating class C; that is, the plate current flows in short pulses. The crystal and plate inductance and capacity are necessary to store the energy in the current pulses. The energy stored in the plate circuit is returned to the grid circuit via the grid-to-plate capacity of the tube. Thus the tube supplies its own input signal and oscillates. The electrical characteristics of the crystal are such that it acts as a very high Q inductance and capacitance combination. A detailed account of oscillator criteria can be found in Cruft (1, p. 482).

The tube used was a 6SJ7 that supplied an output sine wave of 200 volts peak-to-peak amplitude. The crystals used resonated at 2 megacycles and 100 kilocycles per second. An interval of

0.5 microsecond corresponds to a frequency of 2 megacycles per second, while 10 microseconds corresponds to 100 kilocycles per second.

Triode clipper. Triodes are one of the easiest methods of clipping sine waves. They find popular usage in the Radio Corporation of America's synchronizing generator for television. The triode clipper circuit is given in Fig. 4.

The triodes used were contained in the single envelope of a 6SN7. The 200 volts peak-to-peak sine wave from the oscillator stage was impressed on the grids of the first triode. Plate-load resistors of 20,000 ohms were used.

On the positive swing of the input sine wave, the plate current increases until the voltage drop across the load resistor gets large enough to counteract the plate-supply voltage. At this point the potential on the plate becomes too low to attract many electrons from the cathode. Note that the positive grid lines approach the zero plate-voltage line asymptotically in the tube's plate characteristics graph. By this analysis the plate wave form will be flattened when the grid goes positive.

During the negative swing of the sine wave the tube is driven to plate current cut-off. Cut-off of the 6SN7 occurs at a negative-grid potential of 20 volts. The negative 20 volts is located where the grid voltage line intersects the point of intersection of the zero plate-current line and the load line. All points below 20 volts on the negative swing of the sine wave will not appear at the output since no plate current flows during that period.

At the output will appear a square wave. Its amplitude is computed from the product of the plate-current variation and the load resistance. The lowest plate current is 0 and the highest is 14.5 milliamperes.

$$\text{Amplitude} = 20,000 (.0145 - 0)$$

$$= 290 \text{ volts.}$$

While this output is a reasonable square wave, an impressed wave shape would be realized by processing the square wave through the second triode. The operation of the second triode is the same as the first, but here the grid signal is 180 degrees out of phase with the original sine wave due to the inversion effect of vacuum tubes. At the output of the second tube, the square wave present has been clipped by both plate-current saturation and cut-off on each peak.

Differentiating network. Pulses can be derived from a square wave by differentiating the square wave with respect to time. The network used is shown in Plate III, Fig. 1. The circuit differentiates in this manner. The voltage across the series combination of condenser and resistor is given by

$$e(t) = Ri + q/C$$

Make Z and C small so that the q/C term will predominate. Then

$$q = Ce(t)$$

and so

$$i = \frac{dq}{dt} = C \frac{de(t)}{dt}.$$

The voltage across the resistor is, by substitution

$$e_R(t) = Ri = RC \frac{de(t)}{dt}.$$

Thus the voltage appearing at the resistor is proportional to the derivative of the applied voltage.

To produce a very sharp pulse from the square wave, the product of the capacitance and resistance must be much less than the period of the square wave. The output pulses derived from the square wave are shown in Plate III, Fig. 2.

The reason for a short time constant in the RC circuit is so that the ZC combination will discharge very rapidly at the point of reversal of the square wave. The condenser charged during the flat period of the square wave, but the output wave form was a zero during that time since the derivative of a constant is zero. The time of decay of the voltage across the resistor can be found by the following. The current is

$$e = \frac{E}{R} e^{-t/RC}$$

so the voltage across R is

$$E_R = Ri = E e^{-t/RC}$$

at

$$t = 0, e_R = 0$$

At $t = 0.1 T$ (T = the period of the square wave), it would be desirable to have the voltage across the resistor decayed to 37 per cent of its previous value E . The ratio of the time constants is

$$-\frac{t}{RC} = \ln \frac{e_R}{E}$$

Substituting the above considerations,

$$+ \frac{0.1 T}{RC} = \ln .37 = +.995 \approx + 1$$

giving $RC = 0.1 T$

At a pulse period of 0.25 microsecond, the RC time constant should equal 0.025 microsecond. A resistor of 1000 ohms with a condenser of 25 micromicrofarads met this condition. For a pulse period of 10 microseconds, a resistor of 1000 ohms and a condenser of 1000 micromicrofarads was satisfactory.

Results. When these circuits were actually constructed and tested, many unexpected variations in wave forms were experienced. While the sine-wave output from the oscillator was as had been anticipated, the square wave from the clipper was not. At 100 kilocycles per second the output from the clipper was rounded, showing the effects of integration. Integration is the converse of differentiation and can be derived by a similar analysis as that performed on the differentiating network or by referring to Arguimbau (2, p. 139). Integration manifests itself by subduing the high-frequency components of the square wave. The output from the clipper at 2 megacycles per second was even more undesirable since the integrating effects were more pronounced at this frequency. For integration, a series RC combination is used with the output taken across the condenser. The time constant of the RC combination must be at least equal to the period of the wave before the effects of integration will be detrimental to the wave form, Cruft (1, p. 146-148). The integrating network is supplied by the triode's plate resistance in parallel with load resistor and the shunt capacities to ground. Plate resistance equals 50,000 ohms, load resistor was 20,000

ohms, output capacity is 1 microfarad, wiring capacity would be at least 10 micromicrofarads. The input capacity to the next stage might add another 5 micromicrofarads. An RC time constant of 0.23 microsecond would result, which substantiates the wave form's malformation at 2 megacycles per second.

Pentodes were also tried in this application as clippers. They clip in the same manner as triodes. They were tried because of their low grid-to-plate capacities, and, while the effects of differentiation were decreased, the degradation due to integration was still present.

After analyzing and testing these clippers, two methods of eliminating both differentiation and integration seem possible. The use of low values of plate-load resistors would reduce the time constants involved. Values around 1000 ohms might be used, but a corresponding decrease in plate voltage would be needed to prevent exceeding the tube's ratings. Cathode-follower clipping would also tend to eliminate differentiation and integration since the cathode resistor is of a low value. With cathode followers, however, the clipping action is not as sharply defined as that realized with plate-circuit clipping due to the negative feedback inherent in cathode followers.

Multivibrators

Since the triode-clipping method was unsuccessful, Mr. Ford suggested that multivibrators might give a square-wave output suitable for differentiation at both the 10- and 0.5-microsecond intervals. The typical multivibrator circuit is shown in Plate III, Fig. 3.

The circuit operates in the following fashion. The plate current increases in the first tube and impresses a negative signal on the grid of the other tube, since the voltage drop across the first tube's load resistor is increasing. This reduces the plate current in the second tube which drives the grid of the first tube even more positive and so accelerates the action. This action ceases when the second tube's grid reaches plate-current cut-off potential. The circuit remains in this state until the charge on the coupling condenser between the first's plate and the second's grid decays to such a value that plate current in the second tube can flow again. With this, the action is started and progresses until the first tube is cut off. The tubes will alternately conduct and cut off with a repetition frequency determined by the time constants of the coupling condensers and their respective grid resistors. The voltage on the coupling condenser will rise from cut-off potential to zero bias during the tube's cut-off period and is given by

$$e_C = -E_R e^{-t/RC}.$$

The rise is exponential and is determined by the time constant of the condenser and resistor associated with the grid. In the formula, E_R is the voltage through which the grid voltage rises. The time for the grid to rise through E_R to the point where plate current flows again is represented by t . Solving for the period of rise,

$$t = RC \ln - \frac{E_R}{e_C}$$

Here E_R equals the difference between the plate potential when

the first tube is conducting (E_m) and when it is cut off (E_{bb}). The condenser voltage will be E_x when the second tube is cut off. The resistance of the discharge path is represented by R and equals

$$R = R_g + \frac{R_L r_p}{R_L + r_p}$$

where R_g is the grid resistor of the cut-off tube, while R_L and r_p are the load resistor and plate resistance of the conducting tube. The coupling condenser plus stray capacities supply the frequency-determining condenser C .

$$C = C_C + C_s$$

where C_C equals the coupling condenser and C_s is usually assumed to equal the input capacity of the cut-off tube. Another factor to consider is that the voltage across the condenser (E_x) at cut-off will be affected by the voltage divider action of the coupling condenser in series with the input capacity of the cut-off tube. The e_C factor will then be

$$E_x \left(\frac{C_C + C_s}{C_C} \right).$$

Substituting the above factors in the original equation for the period, gives

$$t = \left(R_g + \frac{R_C r_p}{R_C r_p} \right) (C_C + C_s) \ln \frac{(E_{bb} - E_m) C_C}{E_x (C_C + C_s)}.$$

This is the formula used when selecting the proper circuit values for operation at frequencies above 10 kilocycles per second, since at these frequencies the stray capacities cannot be disregarded. Puckle (3, p. 25) gives a splendid account on multivibra-

tors and says that for high-repetition rates the load resistors are reduced so increased plate current will flow, giving more vigorous action and steeper wave fronts and less integration.

Zero-bias multivibrator. The first circuit, using the above formula, was designed for operation with a period t of 0.25 microsecond. The double triode 6J6 was used due to its low interelectrode capacities and relatively low plate resistance. From the Receiving Tube Manual of the Radio Corporation of America, the operating points were determined for the 6J6. Assumed values were: load resistor, 2000 ohms; coupling condenser, 20 micro-microfarads; plate-supply voltage, 250 volts. The plate characteristics graph gave: E_x , -10 volts; E_m , 170 volts; and E_{bb} , 250 volts. The plate resistance of the 6J6 is 7110 ohms, and its input capacity is 2 micromicrofarads. Substituting into the formula for the period, gives

$$.25 \cdot 10^{-6} = (R_g + \frac{(2000)(7100)}{2000 + 7100})(20 + 2)10^{-12} \ln \frac{(250-170)20 \cdot 10^{-12}}{10(20 + 2)10^{-12}}$$

$$.25 \cdot 10^{-6} = (R_g + 1560)(22 \cdot 10^{-12}) \ln \frac{80 (.91)}{10}$$

$$R_g = \frac{.25 \cdot 10^6}{22 \ln 7.4} - 1560$$

$$R_g = \frac{250,000}{44} - 1560$$

$$R_g = 4140 \text{ ohms}$$

Due to the fact that both the load and grid resistors had to be of such a low value with respect to the 6J6's plate resistance, it was felt that a computation of the stage's voltage gain

was in order. From Cruft (1, p. 337), the expression for the voltage gain at any frequency may be written

$$A + \frac{-\mu}{1 + \frac{r_p}{R_L} + \frac{r_p}{R_g} + \frac{C_1}{C_c} + \frac{\omega r_p C_o C_1}{C_c}}$$

$$+ j \frac{-\mu}{\frac{1}{\omega R_g C_c} + \frac{r_p}{\omega R_L R_g C_c} + \frac{r_p C_1}{R_L C_c} - \omega r_p (C_o + C_1)}$$

in which

$$\mu = 38$$

C_1 = grid shunt capacities = 10 mmf

C_o = plate shunt capacities = 5 mmf

C_c = coupling condenser = 20 mmf

r_p = plate resistance = 7100 ohms

R_L = load resistor = 2000 ohms

R_g = grid resistor = 4140 ohms

$\omega = 2\pi f$, $f = 20$ megacycles per second at 10th harmonic
of square wave

Upon substitution it was found that the voltage gain was approximately 2.7.

However, when the multivibrator was constructed and the output viewed on the Browning oscillosynchroscope, it was discovered that no plate or grid alternations were present. This indicated that the assumed stray capacities used in evaluating the voltage gain were too small, and that actually the gain was below 1. A gain greater than 1 is necessary before multivibrator action will occur. Series peaking in the plate circuit might combat these

ills by increasing the high-frequency gain.

Positive bias multivibrator. If the grid resistor is returned to a positive voltage source instead of to ground as previously, the coupling condenser's exponential voltage would rise from $-E_{bb}$ to the positive bias level. This rise would then be much sharper, so that the time between tube cut-off and conduction would be much less. When this method is used, the grid resistor should be at least 1 megohm in size to prevent excessive grid current when the grid is positive. For operation with a period of 0.25 microsecond, a low-grid resistor is needed for the correct time constant. But this cannot be because grid current would flow and multivibrator action would be unobtainable. Many values were tried in the laboratory to find the optimum point. These values were determined by the equation

$$t = (R_g + \frac{R_{Lp}}{R_L + r_p})(C_c + C_s) \ln \frac{(E_{bb} - E_m + E_c) C_c}{(E_x + E_c)(C_c + C_s)}$$

where the new factor E_c is the positive bias voltage.

None of the values tried would give an output wave and it was noted that considerable grid current flowed. Even at 100 kilocycles the grid resistor had to be lower than the 1 megohm needed to prevent grid current.

Potter multivibrator. In Plate IV, Fig. 1, is shown the schematic for a Potter multivibrator.

Tube V_2 acts as a cathode follower. Any change on the grid of V_2 will make a corresponding change in the plate current of V_2 . Since the plate current of V_2 flows through the common cathode resistor, a variation on the grid potential of V_1 will be

effected by the changing of the cathode potential of V_1 . The change of potential on the grid of V_1 will control the plate current of V_1 . Since the plate potential of V_1 is transmitted to the grid of V_2 , regeneration will occur and multivibrator action will result.

The period of the square-wave output from the multivibrator is determined by the time constant of the coupling-condenser and grid-resistor combination, providing the plate-load resistors are small in comparison to the grid resistor. This condition is easily met for small plate-load resistors are also desirable to insure large anode currents and high-frequency response. The cathode resistor is determined from cathode-follower theory. M.I.T. (4, p. 2-53) gives a very complete graphical analysis of a cathode-coupled multivibrator.

In general, square waves with periods shorter than 1 microsecond are extremely difficult to generate in symmetrical multivibrators. The many stray-circuit capacities, high plate currents, and complex circuit configurations for high-frequency response make short period multivibrators impractical.

Clipped Sine Wave, Second Attempt

Sine-wave oscillator. An electron-coupled Hartley-type variable-frequency oscillator was used as the sine-wave source. Its schematic is given in Plate IV, Fig. 2. It is similar to the crystal oscillator mentioned previously except that only one tuned circuit is needed and that the output voltage is fed back to the input via the portion of the coil that plate current flows through.

A 6V6 was used as the oscillating tube to supply a 300-volt, peak-to-peak, sine-wave amplitude. Terman (5, p. 480) has a very inclusive account on oscillators.

Series diode clipper. A series-diode clipping circuit is shown in Plate V, Fig. 1. A germanium-crystal diode was used.

A positive voltage applied to the plate will cause current flow through the diode and series resistor. The resistance of the diode is about 200 ohms when conducting so the greatest portion of the voltage drop will appear across the series resistor. A 10,000-ohm series resistor was used. When a negative voltage is impressed on the plate, very little current will flow, since the diode's back resistance is approximately 100,000 ohms. At 2 megacycles per second, the shunt capacity of the diode must be included. According to Kloeffer (6, p. 183), a germanium diode has a shunt capacity of approximately 3 micromicrofarads. The admittance of the shunt capacity is

$$Y_C = j Z \pi f C = 37.6 \text{ micromhos}$$

and the admittance of the diode's back resistance is

$$Y_R = \frac{1}{100,000} = 10 \text{ micromhos.}$$

The back admittance of the diode would be

$$\begin{aligned} Y &= Y_R + j Y_C \\ &= 10 + j 37.6 \text{ micromhos} \\ &= 39.0 / 75.1^\circ \text{ micromhos} \end{aligned}$$

The back impedance would be

$$Z = \frac{1}{Y} = 25,700 / -75.1^\circ \text{ ohms.}$$

Under these conditions the current flow would not be limited sufficiently to give good clipping. At 100 kilocycles per second, the admittance of the shunt capacity would be reduced by 20 so that reasonable clipping would be expected at this frequency.

A smaller load resistor would change the proportionate voltage drops in the circuit and would undoubtedly improve the clipping action.

This method of clipping is usually used in conjunction with the grid of a subsequent amplifier stage. The grid bias of this stage also supplies the bias for the diode to determine the clipping level. When this source of bias is not available, a separate bias supply is needed and is inserted in series with the diode's load resistor.

Shunt diode clipping. Shunt diode clipping showed desirable characteristics for clipping at 2 megacycles per second. Here, again, a germanium diode was used. Plate V, Fig. 2, presents the schematic for such a clipper.

When a negative voltage is placed on the plate, no conduction will take place in the diode and the output voltage will appear across the shunt combination of the diode's back resistance and the output resistor. A positive voltage on the plate of the diode would cause the diode to conduct, and the output voltage would appear across the low forward resistance of the diode. The series-limiting resistor is used to prevent undue loading of the sine-wave source when the diode is conducting. The value of the series resistor is usually around 25,000 ohms. The load resistor was 100,000 ohms in value. The forward resist-

ance of the diode was 200 ohms and its back resistance was 100,000 ohms. The output voltage with a negative input voltage of 150 volts would be

$$e_o = \frac{(150)(50,000)}{25,000 + 50,000} = 100 \text{ volts}$$

The output voltage with a positive input of 150 volts was

$$e_o = \frac{(150) \left(\frac{(100,000)(200)}{100,000 + 200} \right)}{25,000 + \left(\frac{(100,000)(200)}{100,000 + 200} \right)} = 1.2 \text{ volts.}$$

A positive bias can be placed on the cathode of the diode in order to raise the output voltage during conduction. A positive bias of 10 volts was decided upon for the laboratory test.

This circuit was constructed using the values given above. The output wave forms were viewed on the Browning oscillosynchroscope. At 100 kilocycles per second, some integration of the positive clipped portion of the output wave was noticed. At 2 megacycles per second, the integration of the output was of such a magnitude that the output was unsatisfactory for the subsequent modifications needed. The series-limiting resistor in combination with the shunt capacities of the circuit formed the integrating network. Assuming a shunt capacity of 10 micro-microfarads, including that of the diode, the time constant of the network would be

$$T = RC = 10 \cdot 10^{-12} \cdot 25,000 = .25 \text{ microsecond,}$$

which satisfied the conditions for integration.

Chance, et al (7, p. 331) says: "At the present stage of

crystal development, the uses of germanium crystals are mostly for quasi-selection where some distortion of the wave form is permissible."

However, an improvement of the clipped wave form could be effected by using low-impedance circuits. Methods of utilizing low-impedance clipping would be: feed the clipping diode from a cathode follower, replace the load resistor with the input to a grounded-grid amplifier, and simply use smaller limiting and output resistors.

OTHER METHODS OF PULSE GENERATION

Pentodes operating class C. If a very high-amplitude sine wave is applied to the grid of a pentode, large plate currents will flow during the positive alternation but will be cut off during the negative swing. The grid of the pentode had zero bias and the load resistor was of a low value so that plate saturation would be delayed until the positive swing was near its peak. The plate characteristics of a pentode are such that plate current changes during the large negative grid excursion are small with respect to the current changes during the high positive excursion. The plate-current pulse has a duration of approximately 40 per cent of the total duration of the grid alternation. The circuit for such an arrangement is shown in Plate V, Fig. 3. A load resistor of 1000 ohms, grid resistor of 10,000 ohms, plate voltage of 300 volts, and screen supply of 150 volts were used. With a frequency of 2 megacycles per second impressed on the grid, the output pulses were not steep enough and showed the effects of considerable integration. Integration was caused by the shunt

capacities and load resistance of the 6AG7 tube employed in the circuit. The grid signal was supplied by the 6V6 Hartley oscillator and had a peak-to-peak amplitude of 300 volts.

An interesting circuit was evolved from the above and provides extremely sharp pulses with intervals of 10 microseconds and amplitudes of 50 volts. Its circuit is shown in Plate VI, Fig. 1.

The circuit values were: grid resistor, 500,000 ohms; cathode resistor, 3300 ohms; plate-load resistor, 56,000 ohms; output resistor, 1000 ohms; cathode by-pass condenser, 500 micro-microfarads; screen by-pass condenser, 0.01 microfarad; output condenser, 500 micromicrofarads; screen voltage, 150 volts; and plate-supply voltage, 300 volts. The 6AG7 tube operates class C as before. The current pulses cause positive voltage pulses at the cathode resistor and negative voltage pulses appear at the plate resistor. The cathode resistor is by-passed by the cathode condenser to reduce negative feedback. The cathode condenser is not large enough to by-pass the cathode pulses to ground, however. The current flowing through the cathode resistor places a negative bias on the grid, causing the tube to operate closer to class A conditions. An external bias supply was tried but it did not improve the output wave shape. The output condenser and resistor form a differentiating network that improves the plate pulses.

At 2 megacycles per second, the output wave form was not satisfactory. As before, integration in the plate circuit was the degrading factor. Shunt or series peaking, or network coup-

ling between stages would undoubtedly improve the output wave form. A simpler expedient would be to use smaller load and cathode resistors since the pulses would then appear across a lower impedance than previously.

FINAL DESIGN

In the light of the experiments made on the circuits discussed before, several important design considerations were discovered. For adequate reproduction and formation of these very short duration pulses at high-repetition rates, very low load resistors would have to be used. In fact, the only limit on the smallness of these resistors should be the maximum plate dissipation of the tube in the circuit. Also, where sharp voltage transitions are required, peaking coils would be a necessity. Of course, all lead lengths must be kept at a minimum so as to reduce stray capacities.

A general discussion of the final design will be presented and then followed by a detailed development of each stage.

Plate VI, Fig. 2, shows the block diagram for the pulse generator.

Either a positive or negative trigger may be impressed on the grid of the phase inverter shown on Plate VII as Fig. 1. In the output of the phase inverter is a single-pole, double-throw manual switch which connects the input of the negative gate to either the plate or cathode of the inverter. Since the negative gate requires a positive pulse for triggering, the switch will take a positive pulse from the cathode when a positive trigger is applied to the inverter's grid, or, when a negative trigger

is placed on the grid of the inverter, the switch is thrown to the plate where a positive pulse will appear due to the 180-degree phase shift between the grid and plate signals.

The negative gate is generated by a one-shot multivibrator of the cathode-coupled variety. Its schematic is shown on Plate VII, Fig. 2. Section V_2 is conducting under the monostable condition, while section V_1 is cut-off. The positive pulse on the grid of V_1 drives the grid above cut-off and starts the negative gate which appears at the plate of V_1 . Refer to the Potter multivibrator description given in the CIRCUITS section for a detailed account of the switching operation. The positive bias on the grid of V_1 is incorporated so that only a small amplitude trigger pulse is needed to instigate the negative gate. Note that peaking coils are used in both the plate and cathode of V_1 in order that a sharp negative gate could be obtained.

The negative gate is impressed on the grid of the damping tube. This damping tube is normally conducting since the grid is unbiased. The negative gate drives the tube to cut-off, so now the energy stored in the inductance, L_0 , connected in the cathode oscillates between the inductance and the capacitance at a frequency determined by the size of the inductance and the shunt capacitance. This is commonly called a "ringing circuit". This circuit is given in Plate VIII, Fig. 1.

However, the sine-wave oscillations of the ringing circuit would soon damp out due to the resistance in the circuit unless some energy is reintroduced into the ringing circuit to maintain the oscillations at a constant level. The Hartley oscillator

shown in Plate VIII, Fig. 2, is adjusted by R_1 to supply just the required amount of fed-back energy to maintain oscillation. This oscillator operates as a class A amplifier so very little wave form distortion is present. The tap on the inductance is at the center, making it possible for the class A amplifiers to feed back sufficient energy. Since the truest wave form appears at the grid, the output is taken from this point.

The sine wave is placed on the grid of the clipper via the variable resistor, R_1 , shown in Plate IX, Fig. 1. This potentiometer is used to vary the amplitude of the output pulses. The positive swing of the sine wave on the grid causes a positive pulse to appear at the cathode and a negative pulse at the plate, since this stage operates as a phase inverter also. The clipping action occurs when the grid sine wave goes negative and the plate current is cut off due to the zero grid bias. This action is described in the triode clipper part of the CIRCUITS section. This tube operates in a quasi-class C fashion so that the pulses are of a shorter duration than the input sine-wave's positive excursion. The positive pulse at the cathode is used as one of the final output pulses. The negative plate pulse is transferred to the final cathode follower.

Plate IX, Fig. 2, is the final cathode follower which has a positive bias on its grid so that the negative pulse will not be clipped. The final output negative pulse is taken from this stage's cathode.

Both the positive and negative pulses have amplitudes of 50 volts at a low impedance since they are from cathode followers.

An external power supply was used and supplied 300 volts regulated at 200 milliamperes. The other voltages used throughout the pulse generators were supplied by a voltage divider across the input 300 volts.

Now for the actual design calculations.

Input phase inverter, clipper, final cathode follower.

Tubes of the 6AG7 type were used for these three stages. With 300 volts on the plate, a load resistor of 4000 ohms was the lowest permissible that would still keep the tube's plate dissipation within reason. Two thousand ohms appear in the cathode and 2000 in the plate circuit. For analyzing these stages, a voltage input to voltage output transfer characteristic is drawn in Plate X, Fig. 1. This curve is quite easily found from the load line on the tube's plate characteristics. A value of grid voltage is assumed and the plate current found, since the cathode voltage, which equals the plate voltage due to equal resistors, is equal to

$$E_K = I_b R_K$$

Also, since E_K appears at the grid along with the input voltage, E_{in} , this relation is true:

$$E_{in} = E_c + E_K$$

where E_c is the actual grid voltage. These two equations are evaluated to form the table included in Plate X, Fig. 1. E_K is plotted versus E_{in} for the transfer characteristic. So that both positive and negative triggers will be passed faithfully, the input phase inverter's grid is biased to a +68 volts, which is the center of the transfer curve. This circuit is shown in Plate VII, Fig. 1.

The same logic follows for the clipper shown in Plate IX, Fig. 1. However, in this case, no bias is used since the negative swing is to be clipped. The final output positive pulses taken from the cathode of this clipper appear across an impedance given by

$$Z_o = \frac{r_p + R_p}{\mu + 1}$$

in parallel with R_K , where

$$r_p = .13 \text{ megohm}$$

$$R_p = 2000 \text{ ohms}$$

$$\mu = \mu_m r_p = 1560$$

$$R_K = 2000 \text{ ohms}$$

$$Z_o = 83 \text{ ohms.}$$

This low impedance is very desirable since external apparatus connected to the output terminals should not load the pulse generator excessively.

The final cathode follower is analyzed in the same manner. Here the grid bias is +100 volts, for only negative pulses appear at its grid. The final output negative pulses at the cathode of this stage also appear across an impedance of 83 ohms. Its circuit is given in Plate IX, Fig. 2.

With 50 volts on the grids of these three stages, the output voltages are close to 50 volts due to the slope of the transfer characteristic being near 1 and intersecting very close to the origin. Also, since the transfer curve is quite nearly linear, there is very little distortion in the output.

The values of the circuit components for these stages are

identical.

$$R_p = 2000 \text{ ohms}$$

$$R_k = 2000 \text{ ohms}$$

$$R_2 = 15,000 \text{ ohms}$$

$$R_1 = 100,000 \text{ ohms}$$

$$C_1 = C_2 = C_3 = .01 \text{ micromicrofarad}$$

Negative gate. This circuit is shown in Plate VII, Fig. 2.

A type 6J6 double triode was used because it is especially applicable to high-frequency multivibrators. To analyze this circuit, two load lines are drawn, one for each section, on the tube's plate characteristics. With $R_3 = 10,000$ ohms, $R_4 = 5000$ ohms, and $R_6 = 5000$ ohms, the load line for V_1 will be 15,000 ohms, and 10,000 ohms for V_2 . There are 300 volts for the plate supply.

Before the trigger the following calculations can be made.

In these calculations

$$E_{gk2} = \text{grid-to-cathode voltage of } V_2$$

$$I_{b1} = \text{plate current of } V_2 \text{ at grid voltage} = 0$$

$$I_{b2} = \text{plate current of } V_2 \text{ at grid voltage} = 0$$

$$E_{c2} = \text{grid-to-ground voltage of } V_2$$

$$E_k = \text{voltage across cathode resistor}$$

$$E_{b2} = \text{plate-to-ground voltage of } V_2$$

$$E_{b1} = \text{plate-to-ground voltage of } V_1$$

$$E_{gk1} = \text{grid-to-cathode voltage of } V_1$$

$$E_{pk1} = \text{plate-to-ground voltage of } V_1$$

$$E_{c1} = \text{grid-to-ground voltage of } V_1$$

V_1 is cut-off

V_2 is conducting

$$E_{gk2} = 0$$

$$I_{b2} = 17.5 \text{ ma}$$

$$E_{c2} = E_k = 5(17.5) = 87.5 \text{ volts}$$

$$E_{b2} = 300 - 2(87.5) = 125 \text{ volts}$$

$$E_{b1} = 300 - 87.5 = 212.5 \text{ volts}$$

$$E_{gk1} = -9 \text{ volts for cut-off of } V_1 \text{ when}$$

$$E_{pk1} = 212.5 \text{ V.}$$

To solve for

$$E_{c1} = -E_k + 2 E_{gk1}$$

$$E_{c1} = -87.5 - 18 \approx 70 \text{ V}$$

E_{c1} is supplied by the voltage divider R_1 , R_2 , and makes it possible for a small trigger voltage to instigate the negative gate. This trigger must be at least +9 volts.

When the trigger arrives, the following calculations are possible.

V_2 is cut-off

V_1 is conducting

$$E_{gk1} = 0$$

$$I_{b1} = 14 \text{ ma, when } E_{gk1} = 0 \text{ volts}$$

$$E_k = 5(14) = 70 \text{ V}$$

$$E_{b1} = 300 - 2(70) = 160 \text{ volts}$$

$$E_{c2} = 87.5 - 140 = -52.5 \text{ volts}$$

$$E_{pk2} = 300 - 70 = 230 \text{ volts}$$

$$E_{gk2} = -10 \text{ volts for cut-off when}$$

$$E_{pk2} = 230 \text{ volts}$$

V_2 will again conduct when $E_{c2} = 70 - 10 = 60$ volts. The calculated wave forms are shown in Plate X, Fig. 2. The negative gate is E_{b1} during the conduction of V_1 and equals 140 volts.

The gate duration, which is the period of conduction of V_1 , is given by the product of the coupling condenser C and the grid resistor R_5 . R_5 must be larger than .5 megohm in order to prevent grid current in V_2 since this resistor is returned to $B+$.

To find the correct RC combination

$$e = E e^{-t/RC}$$

where $e = 300 + 52.5 = 352.5$ volts

and $E = 300 - 60 = 240$ volts

for $E_{c2} = -52.5$ volts when V is cut-off

and $E_{c2} = +60$ volts when V_2 again conducts

The condenser C charges from 240 to 352.5 volts during the conduction of V_1 or the cut-off period of V_2 .

Continuing the calculations,

$$-\frac{t}{RC} = \ln \frac{e}{E} = \ln \frac{352.5}{240}$$

$$\text{or } \frac{t}{RC} = \ln \frac{352.5}{240} = .383$$

$$\text{so } RC = \frac{t}{.383}$$

Tabulating the values needed,

t	R	C
Microseconds	Megohms	Micromicrofarads
2.5	0.5	13
5.0	0.5	26
50.0	1.0	130
500.0	1.0	1300

It was decided to have the peaking coils resonate at 2 megacycles. For the plate circuit there was a shunt capacity of 20 micromicrofarads and using the relationship

$$\omega L = \frac{1}{\omega C}$$

it was found that an inductance of .633 millihenry was needed. The cathode-peaking coil shunted by a capacity of 15 micromicrofarads was found to be of .845 millihenry in size. Actually, in the circuit these coils were single pies from a 4-pie, 2.5-millihenry R-F choke. Each pie has an inductance of approximately .5 millihenry and gave splendid results.

Damping tube. The damping tube supplies the energy for the oscillating tank of C_0 and L_0 and acts as a switch to determine the beginning and cessation of the final output pulses. Its plate supply is 100 volts so that the plate dissipation of the tube, a 6AG7, is not exceeded. The grid is normally at zero potential except during the negative gate when the tube is cut off. The damping-tube circuit is shown in Plate VIII as Fig. 1.

The voltage swing, E_0 , of the sine wave generated by the tank circuit in the cathode when the plate current is cut off, is found from

$$\frac{1}{2} CE^2 = \frac{1}{L} LI^2$$

where

$$E = E_0$$

$$I = \text{cathode current}$$

$$C = C_0$$

$$L = L_0$$

$$I = 62 + 7 = 69 \text{ milliamperes.}$$

Substituting

$$E_0 = I \sqrt{\frac{L_0}{C_0}}$$

However, it was desirable that E_0 be greater than 100 volts so that 50-volt pulses could be realized. So

$$110 = 69 \cdot 10^{-3} \sqrt{\frac{L_0}{C_0}}$$

$$\text{and } L_0 = \left(\frac{110}{69 \cdot 10^{-3}} \right)^2 C_0 = 2 \cdot 5 \cdot 10^6 C$$

But the L_0 and C_0 combination must also resonate at a particular frequency. By substituting $L_0 = 2 \cdot 5 \cdot 10^6 C_0$ into

$$\omega L = \frac{1}{\omega C}$$

it was found that

$$C \approx 100 \cdot 10^{-6} T$$

where T is the period of the sine wave. Tabulating these values at predetermined periods,

T	C	L
Microseconds	Micromicrofarads	Henries
0.5	50	$125 \cdot 10^{-6}$
1.0	100	$250 \cdot 10^{-6}$
10.0	1000	$2.5 \cdot 10^{-3}$
100.0	10,000	$25 \cdot 10^{-3}$

Note that the grid voltage of the damping tube must be held below cut-off during the oscillations.

$E_{\text{cut-off}} = -10$ volts at a plate voltage of 100 volts

$E_o = +110$ volts

so that

$E_{\text{negative gate}} > E_o - E_{\text{cut-off}}$

$E_{\text{NG}} > 110 + 10 = 120$ volts

This condition is met since the negative gate from the multivibrator has an amplitude of 140 volts.

R_1 has a value of 100,000 ohms while the coupling condenser C_1 is .01 micromicrofarad.

Hartley oscillator. The Hartley oscillator as shown in Plate VIII, Fig. 2, is needed to supply the energy dissipated in the tank circuit of the damping tube. Just enough energy is fed back into the tank to make up for that lost. This stage operates in the class A regain so that no wave-form distortion is present. A 6AG7 is used in this stage with these values of components:

$R_1 = 10,000$ ohms variable

$R_2 = 15,000$ ohms

RFC = 2.5-millihenry radio-frequency choke

$C_1 = C_2 = C_3 = .01$ micromicrofarad

R_1 is found by trial and error. Its 10,000-ohm value is adequate to cover the range needed for class A operation. The correct setting of R_1 gives an output sine wave of constant amplitude. The output is taken from the grid where the sine wave is quite pure.

Coil calculations. The coil L_0 was designed from formulas given in the easily procured coil tables. The formula used was

$$n = \sqrt{\frac{L}{F d}}$$

where

n = number of turns

L = desired inductance

F = form factor from coil tables

d = diameter of coil form in inches

The coil forms used had a diameter of 1 inch and a winding length of 2 inches. So

$$F = .01$$

$$F d = .01$$

$$\sqrt{F d} = .1$$

and

$$n = \frac{\sqrt{L}}{.1}$$

Tabulating the calculated values for each inductance gives

L	n
Henries	Turns in 2 inches
$125 \cdot 10^{-6}$	112
$250 \cdot 10^{-6}$	157
$2.5 \cdot 10^{-3}$	Use a 2.5-millihenry R-F choke
$25 \cdot 10^{-3}$	1570--layer wound

Number 30 enamel-covered wire was used. The 2-inch winding length is capable of holding 182 turns of No. 30 wire.

Voltage divider. The voltage divider drops the 300 volts from the power supply to the values for the lower voltage requirements. A 4000-ohm, 20-watt resistor drops the voltage to 100 volts, then a 3200-ohm resistor drops it still further to 68 volts. A 6800-ohm resistor bleeds 10 milliamperes from the 68-volt point to ground.

CONCLUSION

This design seems to be an adequate answer to the problem of generating pulses with short intervals for sweep calibration. Because the output is of 50-volt amplitude at an impedance of 83 ohms, it is possible to use this generator with a variety of equipment. Since the negative gate is triggered by a rising pulse and the input phase inverter gives faithful inversion, any trigger source that has a pulse of sharp rise or fall with an amplitude of over 10 volts will give adequate trigger action at the multivibrator. A precaution must be taken, however. The repetition interval of the triggering pulse must be longer than the negative gate. Otherwise, the one-shot multivibrator will operate on a spurious mode.

To anyone contemplating the construction of a similar piece of equipment, the author wishes to give several pointers. Make the actual physical construction very rugged and have plenty of ventilation for the frequency-determining circuits are coils and condensers which are very prone to drift. Also, a voltage-regulated power supply is a prime requisite.

EXPLANATION OF PLATE I

- Fig. 1. The block diagram of a typical equipment set-up.
- Fig. 2. The block diagram for a simple method of pulse generation.

PLATE I

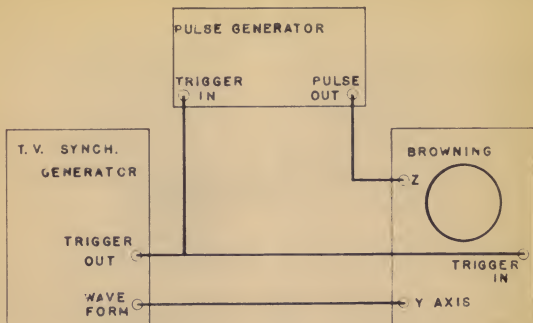


FIGURE 1.



FIGURE 2.

EXPLANATION OF PLATE II

Fig. 1. An electron-coupled, crystal-controlled oscillator.

Fig. 2. A triode clipper.

PLATE II

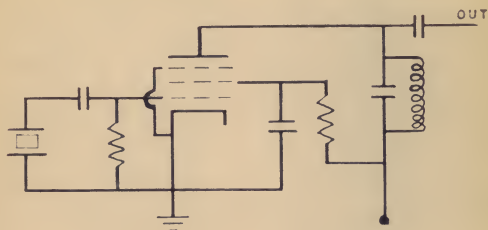


FIGURE 1.

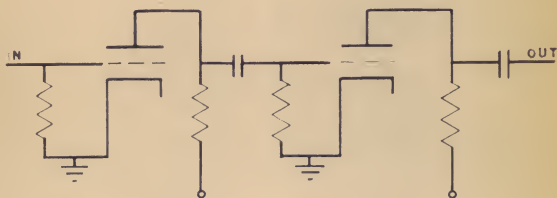


FIGURE 2.

EXPLANATION OF PLATE III

Fig. 1. A differentiating network.

Fig. 2. A - Square wave.

B - Differentiated square wave.

Fig. 3. The typical multivibrator.

PLATE III

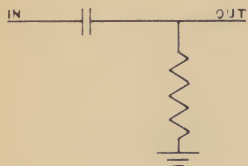


FIGURE 1.

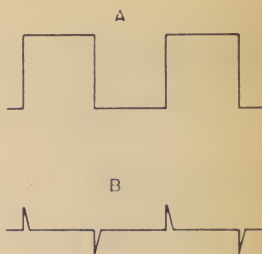


FIGURE 2.

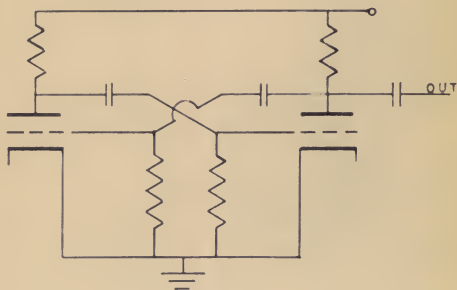


FIGURE 3.

EXPLANATION OF PLATE IV

Fig. 1. The Potter multivibrator.

Fig. 2. A Hartley oscillator.

PLATE IV

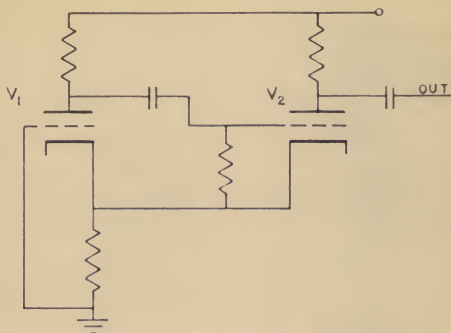


FIGURE 1.

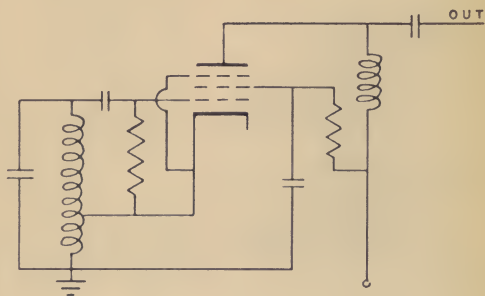


FIGURE 2.

EXPLANATION OF PLATE V

Fig. 1. A series-diode clipper.

Fig. 2. A shunt-diode clipper.

Fig. 3. A zero-bias pentode in quasi-class C operation for pulse formation.

PLATE V

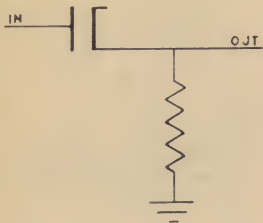


FIGURE 1.

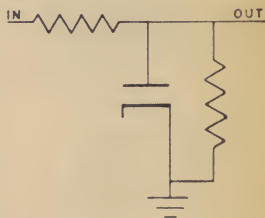


FIGURE 2.

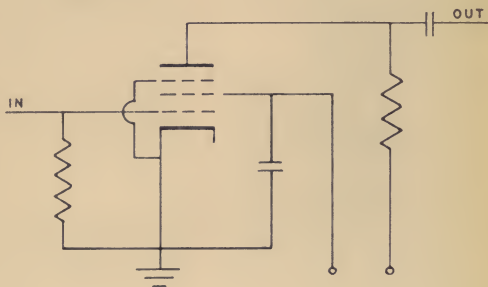


FIGURE 3.

EXPLANATION OF PLATE VI

- Fig. 1. A pentode as cathode follower in quasi-class C operation for positive and negative pulse formation.
- Fig. 2. The block diagram for final design of pulse generator.

PLATE VI

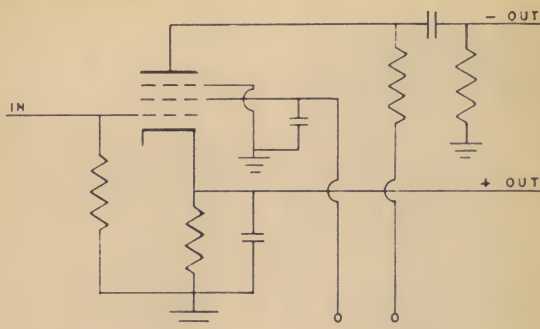


FIGURE 1.

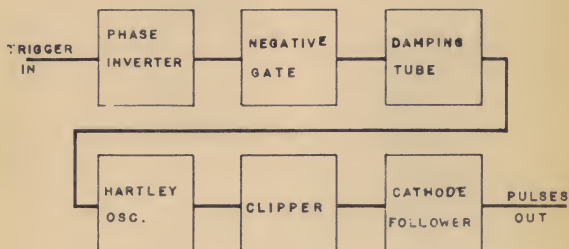


FIGURE 2.

EXPLANATION OF PLATE VII

Fig. 1. Cathode-follower phase inverter.

Fig. 2. One-shot, cathode-coupled multivibrator for negative gate.

PLATE VII

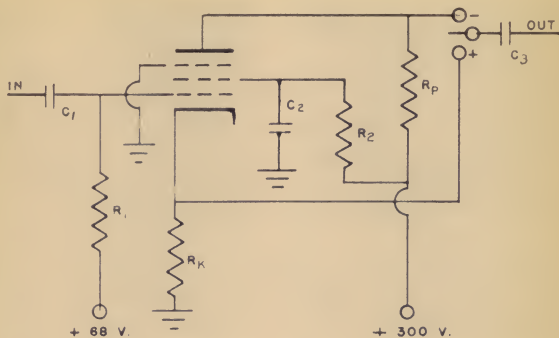


FIGURE 1.

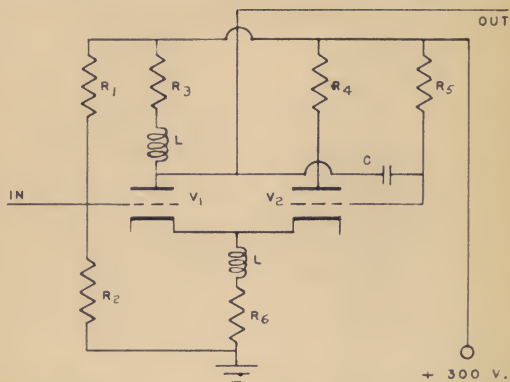


FIGURE 2.

EXPLANATION OF PLATE VIII

Fig. 1. Damping tube.

Fig. 2. Hartley oscillator.

PLATE VIII

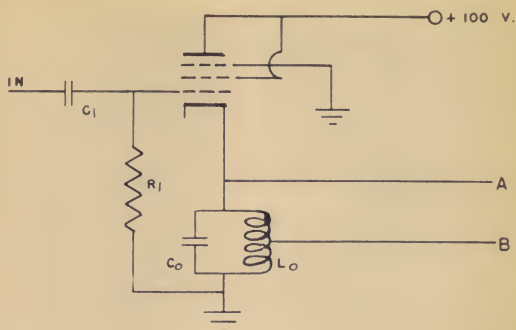


FIGURE 1.

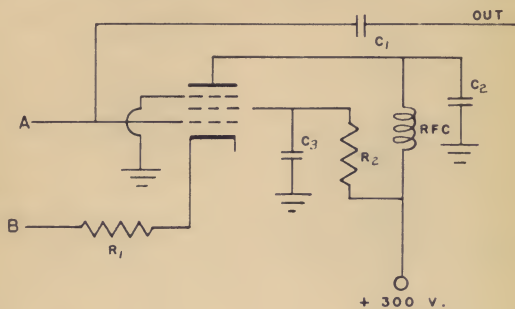


FIGURE 2.

EXPLANATION OF PLATE IX

Fig. 1. Cathode-follower clipper and positive pulse output.

Fig. 2. Cathode-follower, negative-pulse output.

PLATE IX

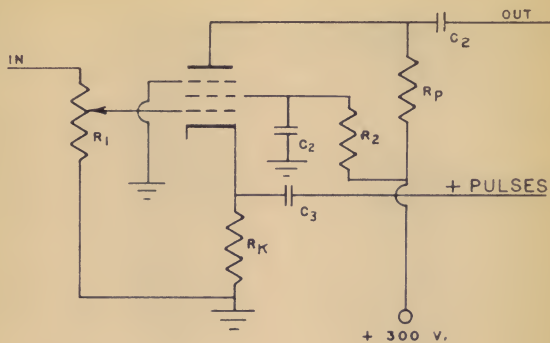


FIGURE 1.

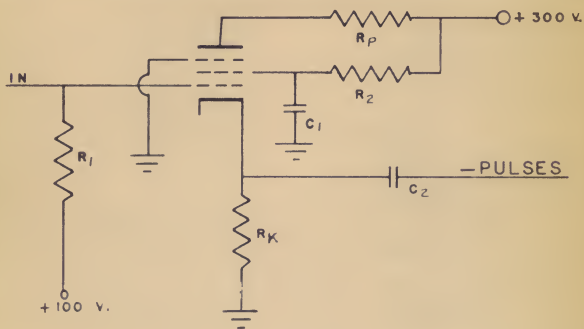


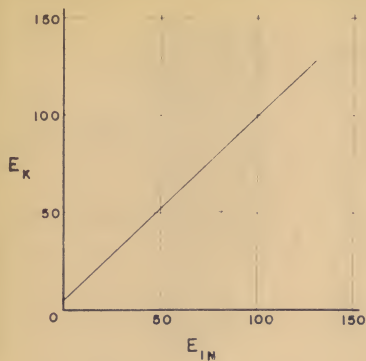
FIGURE 2.

EXPLANATION OF PLATE X

Fig. 1. Transfer characteristic of 6AG7 cathode-follower phase inverter.

Fig. 2. Calculated wave forms in one-shot multivibrator.

PLATE X



E_C	E_K	E_{IN}
+2	128	130
0	120	120
-3	56	53
-6	12	6

FIGURE 1.

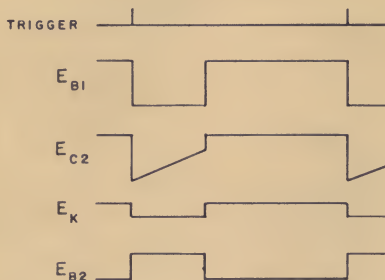
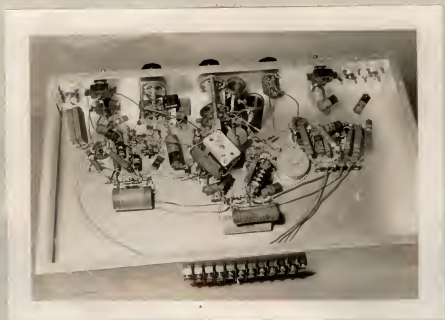


FIGURE 2.

EXPLANATION OF PLATE XI

Photographs of pulse generator.

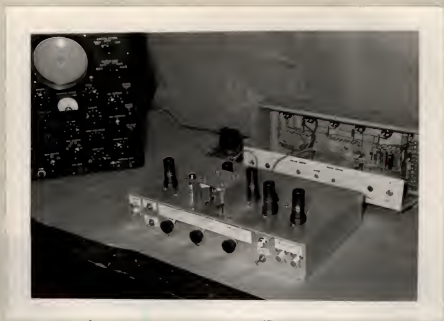
PLATE XI



EXPLANATION OF PLATE XII

Photographs of pulse generator.

PLATE XII



EXPLANATION OF PLATE XIII

Fig. 1. Positive output pulses as viewed on Browning oscillosynchroscope. The pulse has an interval of .5 microsecond. The triggered sweep of the Browning is 1.0 microsecond per inch.

Fig. 2. Positive output pulses with interval of 1.0 microsecond viewed against the triggered sweep of 1.0 microsecond per inch.

NOTE: The negative output pulses are the same as those shown here, but inverted.

PLATE XIII

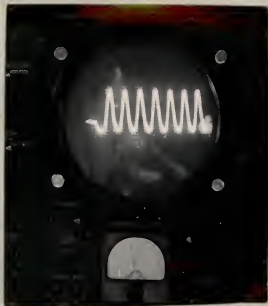


Fig. 1.

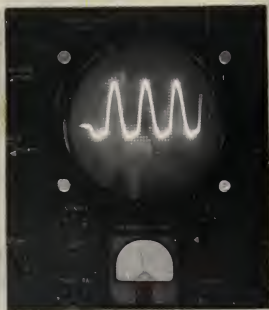


Fig. 2.

EXPLANATION OF PLATE XIV

- Fig. 1. Positive output pulses with interval of 10 micro-seconds viewed against the 20-microsecond-per-inch triggered sweep.
- Fig. 2. Positive output pulses with interval of 100 micro-seconds viewed against the 200-microsecond-per-inch triggered sweep.

NOTE: The negative output pulses are the same as those shown here, but inverted.

PLATE XIV



Fig. 1.



Fig. 2.

ACKNOWLEDGMENTS

The author thanks Professor J. Edmond Wolfe for his many valuable comments and ideas, without which this pulse generator could not have been successfully completed. To Professor W. R. Ford goes the author's sincere gratitude for his ever-present assistance. Mr. H. W. Schultz, Jr. was helpful in innumerable ways.

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A PULSE GENERATOR FOR SWEEP CALIBRATION

by

DON CARROLL GANSCHOW

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of Agriculture and Applied Science, 1950

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Department of Electrical Engineering

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1951

A PULSE GENERATOR FOR SWEEP CALIBRATION

The pulse generator was constructed to be used as a piece of auxiliary test equipment in the Television Laboratory.

There were three methods of pulse generation that seemed particularly applicable to this problem. One method was to clip sine waves and then differentiate the square wave produced. Another method was to generate a square wave with a multivibrator and then differentiate this square wave for the desired pulses. Finally, the amplification of a sine wave by a class C amplifier would give pulses with durations shorter than the positive swing of the input sine wave. For sine-wave clipping, diode, triode, and pentode clippers were constructed and tested. In testing the multivibrators, positive grid return, negative grid return, and cathode-coupled multivibrators were investigated. Pentodes were used for the class C amplifier and with small load resistors they showed the most promising results. At the high pulse frequencies required, all the circuits showed the effects of integration on the output pulses. For proper pulse formation and reproduction, small load resistors were mandatory and where sharp transitions were required, such as in multivibrators, peaking coils would have to be incorporated in the circuits.

Utilizing the knowledge gained by constructing and testing each of the above mentioned circuits, a final design was drawn up and built. Stage-by-stage, it progresses as follows. Either a positive or negative trigger applied to the grid of the first stage is transformed into a positive or negative pulse by the

phase-inverter action of stage one. A switch in the output selects the positive pulse that is used to trigger stage two. The second stage is a cathode-coupled, one-shot multivibrator. The trigger causes a negative square wave at the output that is called the "negative gate". This negative gate is impressed on the grid of stage three. Stage three is conducting and stores energy in the cathode-tank circuit of stages three and four. When the negative gate arrives, it cuts off stage three and allows the stored energy in the tank circuit to oscillate. The frequency of oscillation determines the frequency of the output pulses. The fourth stage is connected to the tank circuit as a Hartley oscillator that feeds energy back into the tank, and thus maintains the oscillations. The oscillations continue as long as stage three is cut off. The sine-wave oscillations from stages three and four appear at the grid of stage five. In stage five, which is a class C amplifier and phase inverter, only the positive excursions of the sine wave are amplified. At the cathode the positive output pulses appear across a low impedance. The negative pulses formed at the plate of stage five are amplified in stage six where the negative output pulses appear across the low impedance of its cathode. The performance of this pulse generator is quite adequate for a multitude of applications. The trigger needed to instigate the pulses insures proper synchronization with all external apparatus. The negative gate determines the duration of the series of output pulses and permits durations of 2.5, 5, 50, and 500 microseconds. The positive and negative output pulses have intervals of .5, 1, 10, and 100 microseconds, and appear across impedances of 85 ohms.