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MODIFICATION OF A SEMI-PRECISION RANGE-DELAY CIRCUIT FOR OPERATION AT HIGH DUTY CYCLES

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MODIFICATION OF A SEMI-PRECISION RANGE-DELAY CIRCUIT FOR OPERATION AT HIGH DUTY CYCLES

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May 16, 1949

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ABSTRACT

In one of the best basic semi-precision range-delay circuits using an accurately compensated sawtooth generator as a time base, operation of a unit designed for a 100,000-yard maximum delay was limited to duty cycles below 50% at the usually desired accuracy of 0.1% -- a serious limitation particularly at long ranges. Modification was undertaken to extend satisfactory operation to duty cycles up to 80%, almost the limit of stable operation for readily available components outside the sawtooth generator.

In its original form, the circuit displayed range errors as great as ±2.5% of the maximum range at an 80% duty cycle. Results obtained with various clamping circuits and other modifications (of the gate generator, of the coupling circuit, of the output circuit, of the sawtooth generator) led finally to an optimum arrangement involving addition to the original six-tube circuit of no more than three miniature tubes. Errors for a maximum delay of 100,000 yards were thereby reduced to ±0.05% with no loss of linearity or stability and to ±0.02% with a 2:1 increase in sensitivity to supply voltages -- both for slow variations in PRF and for rapid frequency modulation.

Performance data for the original circuit and for seven modified circuits are tabulated together for ready comparison.

PROBLEM STATUS

This is a final report on one phase of this problem; work is continuing on other phases.

AUTHORIZATION

NRL Problem No. R05-16D

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MODIFICATION OF A SEMI-PRECISION RANGE-DELAY CIRCUIT FOR OPERATION AT HIGH DUTY CYCLES

INTRODUCTION

One of the best basic semi-precision range-delay circuits developed is that which employs an accurately compensated sawtooth generator and a pick-off diode adjusted by a precision potentiometer. The sawtooth generator may take a number of different forms depending on the exact requirements to be satisfied. Where good stability and high accuracy are needed, and simplicity is not a primary consideration, a gated sawtooth generator using feedback compensation of the "bootstrap" type has been found to be the most satisfactory. If maximum accuracy is required, a linearity of ± 0.1% may be obtained by applying both linear and integrated feedback.

The circuit is not critical as to tube characteristics and has good stability with respect to plate supply and filament-voltage variations. In its commonly used form, however, it has the weakness of relatively slow recovery. In a unit designed for a 100,000-yard maximum delay, operation is limited to duty cycles below 50% if 0.1% accuracy is desired. At long ranges, where a PRF corresponding to 100% duty cycle may still be lower than desirable, a 50% limit is a serious one.

Since an accurate coarse delay circuit is required in range circuits based on the Meacham principle (the only precision ranging devices currently available), it was felt that a high duty cycle R.C. delay circuit would be valuable. No other proposed sawtooth generator fulfilled both accuracy and stability requirements as well as did the arrangement discussed above. It was therefore decided to attempt modification of this basic circuit for high duty cycle operation with no appreciable loss of accuracy and with as little sacrifice of stability as possible.

Modified circuits were tested at duty cycles up to 80%. By reducing sawtooth amplitude to maintain linearity, it was found possible to reduce the maximum range-delay errors from ± 2,500 to ± 430 yards in 100,000 at 80% duty cycle* without adding components to the original circuit. Addition of two triodes, two diodes, and three resistors reduced errors to ± 80 yards with no loss in stability and with a return to the original sawtooth amplitude. A second circuit, adding three triodes and two resistors and a 100-volt negative supply, reduced errors to ± 50 yards in 100,000 with equal stability. In a third modification, two triodes, three diodes, one VR tube, and four resistors were added and a negative supply employed.

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* *Error figures apply for PRF modulation at any frequency as well as for slow changes.*

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This circuit reduced the range delay error to ± 20 yards at 80% duty cycle with a maximum increase in sensitivity to supply voltages of 2:1. The original sawtooth amplitude was employed.

All diodes and triodes added were sections of miniature dual tubes. Since 80% represented nearly the limit of stable operation for components outside the sawtooth generator, no measurements were made at higher duty cycles. However, range errors should be expected to increase rapidly above 80% for any of the circuits listed. The last two modifications discussed are the only ones which could be recommended for use where discharge times were appreciably shorter.

CHARACTERISTICS OF THE BASIC DELAY CIRCUIT

The basic components of the semi-precision range-delay circuit being considered are shown in Figure 1. The gate generator produces a negative gate equal in duration to the maximum range delay required plus any inherent circuit delays. The front edge of the gate starts the linear

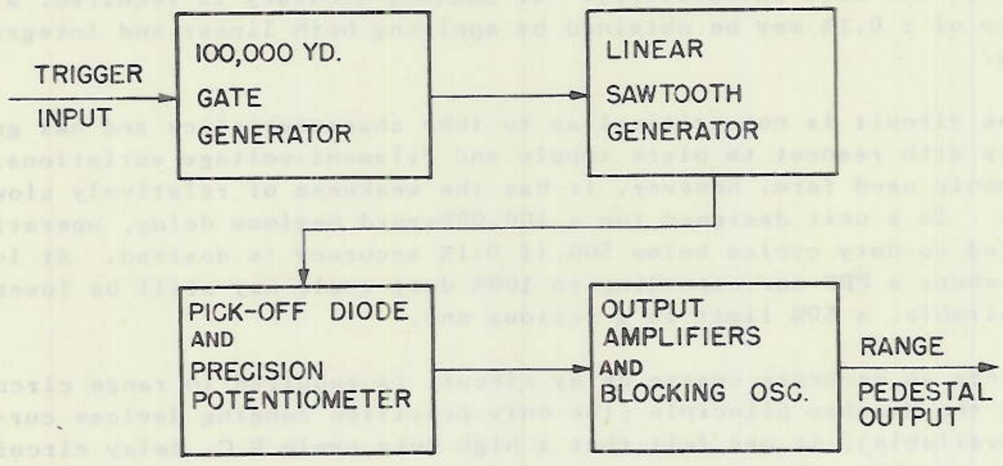

Figure 1- Semi-precision range-delay circuit

charging cycle of the sawtooth generator, and the back edge initiates the recovery or discharge period. The voltage between the cathode of the pick-off diode and ground is set by means of the precision potentiometer, and the plate of the diode driven by the output of the sawtooth generator.

The pulse, produced when the sawtooth reaches the set cathode level and the diode conducts, is amplified and used to trigger the pedestal blocking oscillator. Thus is obtained an output pulse which is delayed from the front edge of the gate by an interval depending on potentiometer setting. The range delay will be a linear function of potentiometer shaft rotation within the limits set by sawtooth-voltage linearity and the rotation-resistance characteristic of the potentiometer.

A circuit of this type, employed as the coarse delay circuit of a 100,000-yard precision-range unit, is shown in Figure 2, the various

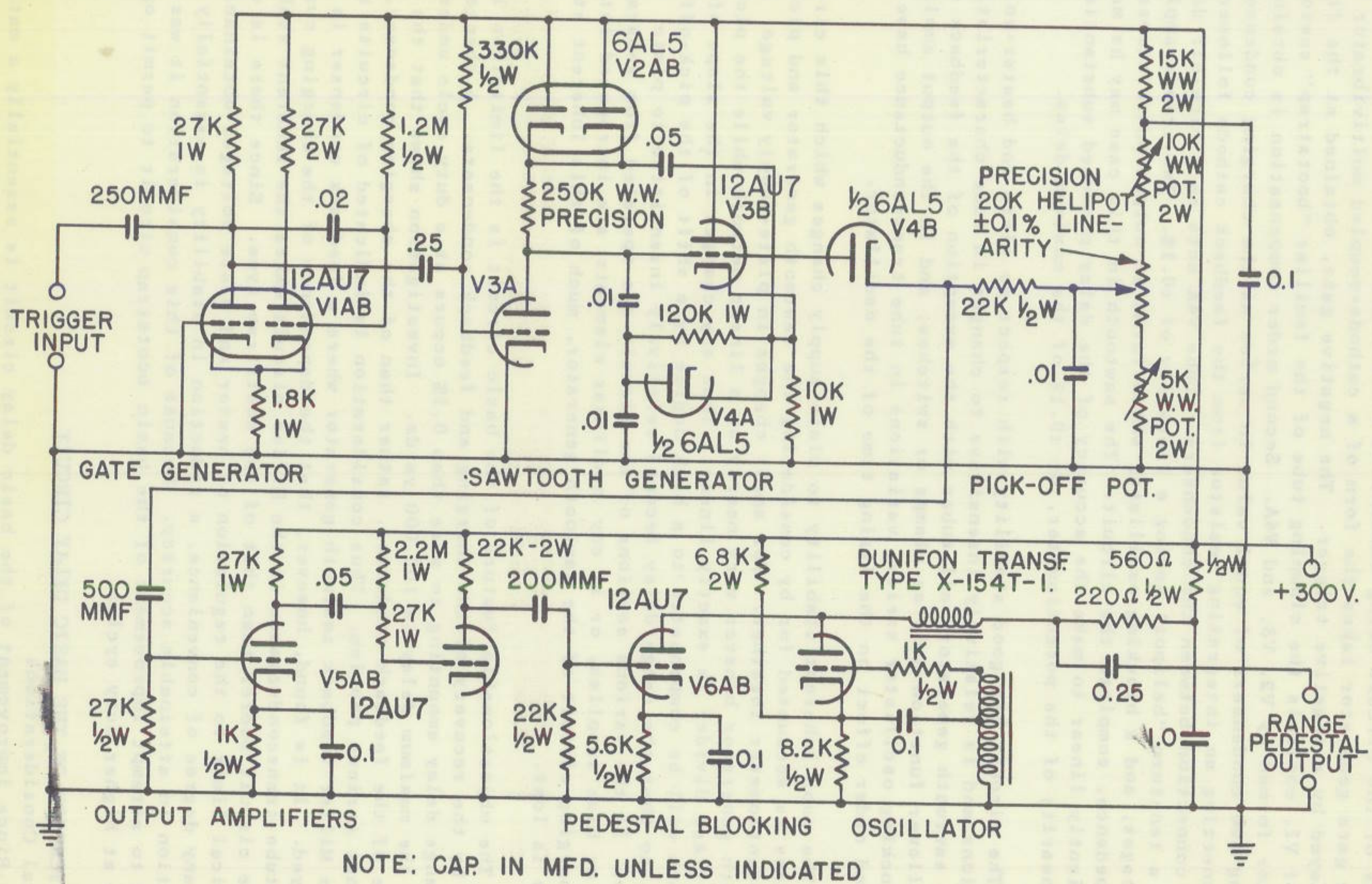

Figure 2- Semi-precision range-delay circuit

sections of the circuit being identified according to the blocks of Figure 1. The gate generator takes the form of a cathode-coupled multivibrator plate-keyed by a negative trigger. The negative gate, obtained at the first plate of VI, controls the clamping tube of the familiar "bootstrap" sawtooth generator formed by V2, V3, and V4A. Second order compensation is obtained by using two condensers of equal value in series as the charging condenser and connecting an integrating resistor from the feedback cathode follower to the connection between the condensers. Tube V4A acts as a pick-off diode set by a ten-turn "helipot" having a linearity of ±0.1%. Two triode amplifier stages, and a blocking oscillator which forms an output pulse across a low impedance, complete the circuit. The sawtooth in this case may be made sufficiently linear to make the accuracy of the delay produced substantially the linearity of the potentiometer, or ±0.1% of the maximum delay.

The circuit has good stability with respect to plate and heater-voltage variations and is relatively insensitive to changes in tube characteristics. In the sawtooth generator, all tubes with the exception of the feedback cathode follower function only as clamps or switches; and in the output amplifier and blocking oscillator series, variations in tube transconductance have only a second order effect on the firing time of the oscillator.

The good inherent stability to plate-supply changes which this circuit possesses is accounted for by considering the sawtooth generator and pick-off potentiometer together. For small changes in plate-supply voltage, the sawtooth generator behaves very nearly as a linear network while the pick-off voltage divider is exactly linear. Thus any changes in the slope of the sawtooth will be compensated to a high degree by a shift of the pick-off point, so that the range delay becomes relatively insensitive to plate supply. If the various sections of the circuit are operated from separate plate or bias supplies, or if any nonlinear elements are introduced into the charging circuit of the sawtooth generator, much of this inherent stability is lost.

The objectionable feature of the basic circuit is the limitation imposed by the recovery of the charging and feedback condensers. A change in the range delay amounting to more than 0.1% occurs at a duty cycle under 50% where the maximum delay is 100,000 yards. Investigation shows that the discharge of the feedback condenser, rather than of the charging condenser, is the most serious problem. Thus consideration is indicated of circuits such as the Miller feedback sawtooth generator where a feedback condenser is not employed. It is found, however, that the dependence of the charging current upon tube transconductance in the Miller circuit makes the inherent stability of the circuit poorer than that of the bootstrap type. Since there is a practical limit to the regulation of heater and plate voltages obtainable with any degree of convenience, a reduction in stability is essentially a reduction in attainable accuracy. Because of this consideration it was decided to attempt improvement of the basic bootstrap circuit to permit operation at higher duty cycles.

MODIFICATION OF THE BASIC DELAY CIRCUIT

General Considerations

Since improvement of the basic delay circuit is essentially a matter of improving the recovery characteristics of the sawtooth generator, a number of different circuit arrangements for this device were considered. These included schemes in which direct-coupled amplifiers and phase inverters were inserted in the feedback loop to eliminate the feedback condenser. No scheme was devised, however, which retained the stability and linearity of the original circuit without unreasonable complication. The use of a voltage-regulator tube as a coupling device in place of the feedback condenser was also proposed and was tried experimentally. There resulted some reduction in error at very high duty cycles where the discharge of a feedback condenser would be very far from complete. At lower duty cycles, however, the variation in regulator drop with variation of average current as the PRF was changed caused range-delay errors larger than those occurring in the condenser-coupled circuit. In addition, a serious objection to the use of a nonlinear element such as a voltage-regulator tube is the loss of stability to plate-supply changes. As explained earlier, the original circuit owes its good characteristics to the fact that the sawtooth generator and pick-off potentiometer together constitute a network essentially linear. The introduction of the VR tube in the feedback loop upsets this condition, thereby causing the charging current to vary with plate supply in a non-linear manner while the pick-off voltage remains a linear function. There results a stability many times poorer than that of the original circuit.

These considerations indicate that no radical circuit changes offer a satisfactory solution to the problem of high-duty-cycle operation. The only remaining approach is the improvement of the recovery time of the original circuit in a way which will not disturb the circuit during the charging cycle. This is essentially a problem in developing improved clamping circuits which will operate to discharge both the charging and feedback condensers more effectively. Consequently, all experimental work was directed toward this approach. The linearity of the sawtooth generator in the best modified circuits should be as good or slightly better than that in the original circuit, since the operating conditions during the charging cycles are either identical or favor the modified case where the feedback can be made more nearly unity. Because of this close correspondence, experimental comparisons of linearity were not made.

In the course of the experimental program the need was discovered for circuit improvements outside the sawtooth generator. Results obtained as the discharge time-constants were progressively shortened indicated that important sources of error must exist other than incomplete recovery of the generator itself. The most serious errors were found to be connected with the coupling of the negative gate from the gate-generating multivibrator to the grids of the clamping tubes in the sawtooth generator. These range-delay shifts were so large that under many conditions they overshadowed all other effects. Some error was also shown to be contributed by the output amplifiers and pedestal blocking oscillator, although the range-delay shifts produced were much smaller than those caused by gate-coupling effects. Both coupling effects and amplifier and blocking-oscillator shifts were reduced to second order errors by fairly simple circuit changes. Thus, the limiting factor in high-duty-cycle operation was, as first supposed, found to be the discharge of the condensers of the sawtooth generator.

A modified form of the circuit of Figure 2 is presented in Figure 3. One form of modified sawtooth generator is shown, and all desirable changes outside the sawtooth generator are included.

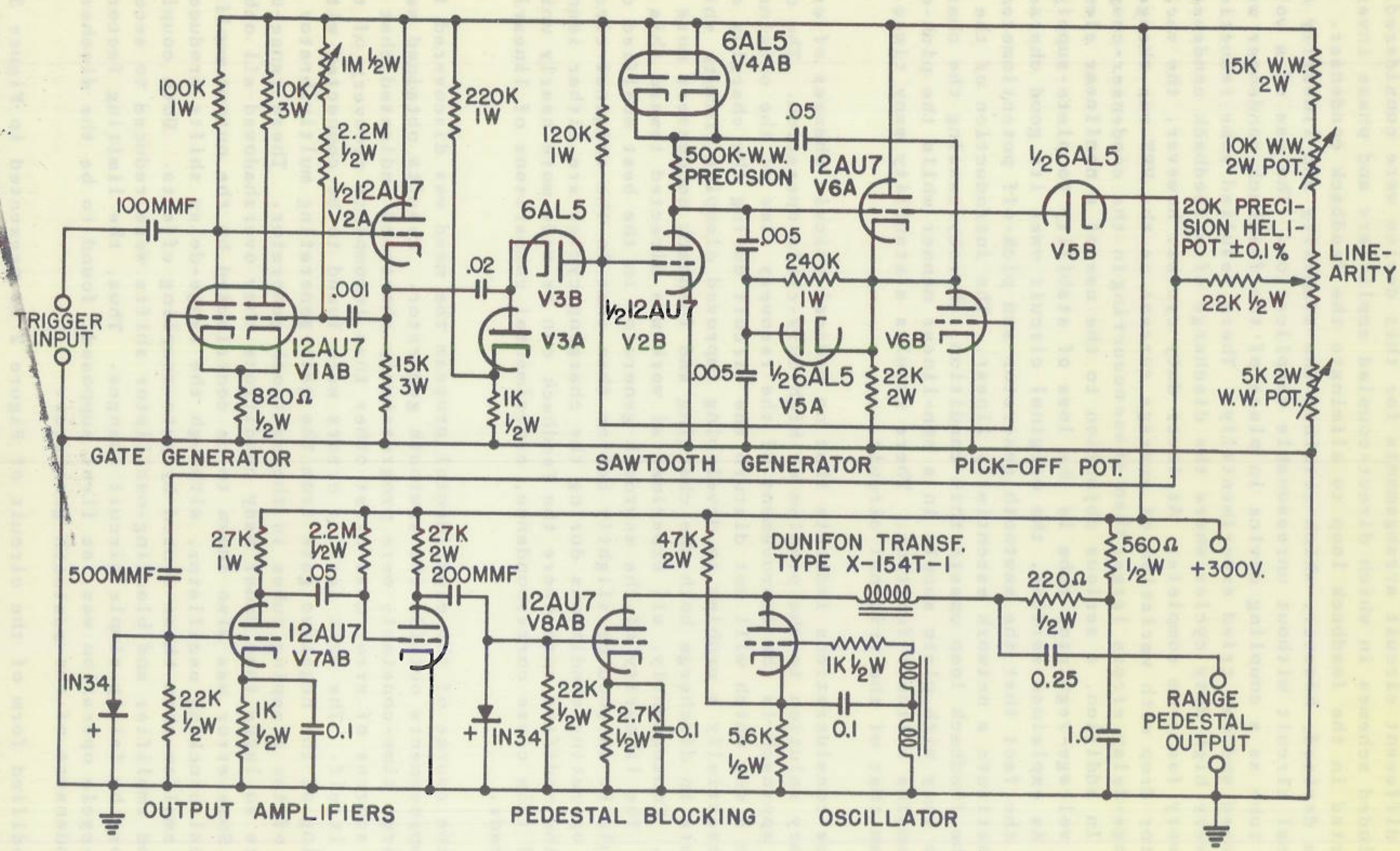

Figure 3- Modified semi-precision range unit

Gate-Generator Changes

The two-tube servel multivibrator employed as a gate generator in the circuit of Figure 2 was found unsatisfactory for operation at high duty cycles. The gate produced shortened excessively, and the circuit frequency-divided between 60 and 70%. Since performance data for the entire delay circuit was desired at duty cycles approaching 80%, the gate generator was changed to a three-tube multivibrator using cathode-follower coupling. This circuit operated up to 85% with gate shortening of only a few percent. In addition, the cathode follower provides a relatively low impedance output for a negative gate. Further refinements in the gate generator are possible, but only at a cost of greatly increased complication. Therefore, the three-tube circuit was used for all experimental work, and data were taken only up to 80% duty cycle to insure stable operation.

Coupling-Circuit Modification

Originally the means of coupling the gating pulse to the clamping tube was not considered to be a first order source of range-delay error. However, preliminary experiments with shortened clamping time-constants did not produce the expected reduction in errors, and the RC gate-coupling circuit was found to contribute most of the residual range-delay shift. The first experimental data were taken with the circuit of Figure 2 unchanged except for the substitution of the three-tube gate-generating multivibrator and the use of a 5,000-ohm cathode-follower load. Under this condition, a range-delay shift of over +1500 yards was observed at zero range setting and over +2000 yards at the maximum delay of 100,000 yards where the duty cycle was increased from 25% to 80%. This error, much greater than would be expected from the discharge time-constants of the sawtooth generator, was traced to dependence on clamping-tube grid circuit for d-c restoration in the gate-coupling circuit. Here the average grid current will vary with the duty cycle of the negative gate. With a long coupling time-constant, increased grid current will flow during the entire discharge interval, and consequently the clamping current at the beginning of the linear charging period will depend upon the duty cycle. Thus large errors will be produced at both minimum and maximum range settings.

The most economical solution of the coupling problem is the use of a smaller coupling condenser which will allow the grid-current transient in the clamping tube to decay to a low value before the end of the discharge period. The possible reduction in coupling capacity is limited by the low-resistance positive grid return needed for effective clamping and the ability of the gate generator to furnish a high discharge current for a short time rather than a low average current. Thus, the high plate load of the two-tube multivibrator of Figure 2 prohibits any significant reduction in the coupling condenser. In the three-tube circuit, however, the cathode follower will supply much larger discharge currents, and the coupling condenser may be reduced until nearly 100% charging occurs during the time of the gate. In actual operation, some value short of this minimum will be found which represents the best compromise between high initial loading of the gate generator and rapid decay of the grid-current transient. In the case under discussion, the optimum coupling was 0.01 to 0.02 μfd for a 330,000-ohm positive grid return and a 100,000-yard gate. The use of this coupling reduced the shift at maximum range to slightly over +500 yards as compared to +2000 yards in the original circuit and made the minimum range shift negligible.

A further reduction in error may be made by using a coupling circuit in which the clamping-tube grid-current is made completely independent of duty cycle. Two coupling circuits were used successfully to accomplish this result. One employs a dual diode and the other a direct-coupled triode operated from a negative supply.

The diode coupling circuit is illustrated in Figure 3. Here one diode is used for coupling and the second for d-c restoration. The return of the d-c restorer to a positive bias of about 1.5 volts insures that the coupling diode is nonconducting except during the negative gate. Thus the operating condition of the clamping tube does not depend on the duty cycle of the gate. A fairly small coupling condenser is used to allow some loss of voltage during the time of the gate. This causes the clamping-tube grid to be carried back to zero bias during the fast initial rise of the gating pulse rather than during the final slow portion of the pulse, which latter is more dependent on the duty cycle at which the multivibrator is being operated. The use of this coupling circuit completely eliminated shift of clamping-tube bias so far as any observable effect on range-delay shift of the original sawtooth generator was concerned. The delay shift of the original sawtooth generator (Figure 2) was further reduced from +500 to +360 yards at maximum range, while minimum range shifts remained very small. The residual +360-yard error is accounted for by incomplete recovery of the feedback condenser in the sawtooth generator.

The combination of three-tube multivibrator and diode coupling is an adequate gating circuit under many conditions. But it falls short of an ideal circuit because the starting time of the sawtooth generator still depends to some extent upon the waveform of the gate pulse, and this waveform becomes more and more dependent upon the duty cycle of the gate generator as external loading increases. For a positive clamping-tube grid return no lower than 120,000 ohms, starting time errors are still low, but appreciably lower values of grid-return resistance cause rapidly increasing shift of sawtooth starting time with PRF. This consideration led to the choice of a 120,000-ohm grid return in the circuit of Figure 3. A lower value of resistance would shorten the discharge time constants of the sawtooth generator, but the reduction of range-delay error obtained would be more than outweighed by the increased variation of starting time with heavier multivibrator loading. One method of overcoming this limitation is through the use of a buffer amplifier between the multivibrator and the sawtooth generator.

A successful method of triode coupling is shown in Figure 4. This circuit makes it possible to employ profitably a clamping-tube grid return of 47,000 ohms as compared to 120,000 ohms for the diode circuit. This results in a very substantial improvement in range-delay shift where the clamping tubes are to be operated with the cathodes at ground potential. A small starting-time shift still exists, and for the 12AU7 tubes employed, it becomes the predominant source of error for grid returns much lower than

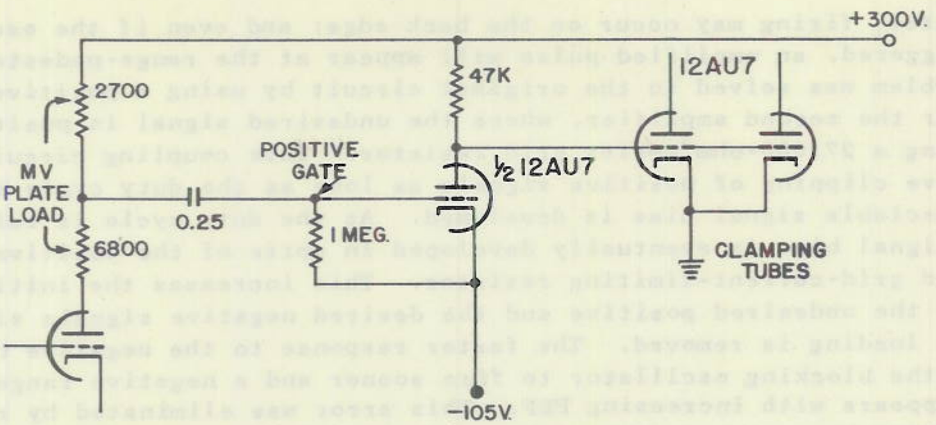

Figure 4 - The triode gate-coupling circuit

47,000 ohms. A positive gate input is needed in this circuit, but since the impedance level is high and the required amplitude low, the signal is easily obtained at a tap on the plate load of the multivibrator. The loading of the multivibrator under this condition is less than that for a diode circuit using a grid return as high as 330,000 ohms. The operating condition of the gating tube is not critical, since it is biased beyond cut-off during the conducting period of the clamping tubes and gates the clamping tubes beyond cut-off during its own conducting period. Thus the voltage of the negative supply is not critical and it need not be well-regulated. In the circuit of Figure 4, signal bias is depended on to keep the gating tube cut off between input pulses. Since the grid time constant may be made very long, this is satisfactory except at extremely low gating duty cycles.

Output-Circuit Modification

The pick-off potentiometer and the output amplifier and blocking oscillator group were both found to contribute some range-delay shift with varying PRF (original circuits, Figure 2; modified forms, Figure 3). The 0.1-mfd bleeder de-coupling condenser shown in Figure 2 was found to cause a ±120-yard shift of the range delay at 80% duty cycle and a 100,000-yard delay setting. Shifts were smaller at lower range settings and negligible at minimum range. The 0.01-mfd by-pass at the potentiometer tap was found to cause negligible range shifts. In the experimental circuit used for performance tests, it was found possible to remove the 0.1-mfd by-pass without introducing jitter or hum modulation of the range delay. Care in wiring layout should make this possible in most cases. Also, if a sufficiently large resistance can be inserted between the by-passed point and the positive end of the helipot, the condenser charging currents will be reduced and the change in voltage level with PRF will be small.

The two output amplifier stages were found to cause a shift in the range delay of -105 yards at 80% duty cycle for any range setting. This error was traced to variations of the grid bias of the second stage with PRF. The design of these amplifiers is complicated by the large negative pulse which appears at the input during the discharge period of the sawtooth generator. If this pulse is allowed to reach the keying tube of the blocking oscillator, firing may occur on the back edge; and even if the oscillator is not triggered, an amplified pulse will appear at the range-pedestal output. The problem was solved in the original circuit by using a positive grid return for the second amplifier, where the undesired signal is positive, and inserting a 27,000-ohm series grid resistor. This coupling circuit causes effective clipping of positive signals as long as the duty cycle is low and no appreciable signal bias is developed. As the duty cycle is raised, however, signal bias is eventually developed in spite of the positive grid return and grid-current-limiting resistor. This increases the initial response to both the undesired positive and the desired negative signals since grid current loading is removed. The faster response to the negative trigger causes the blocking oscillator to fire sooner and a negative range-delay error appears with increasing PRF. This error was eliminated by removing the 27,000-ohm series grid resistor and clipping the undesired signal at the grid of the first amplifier with a crystal diode. When this is done, only a very small bias shift occurs at duty cycles above 80%, and the resulting range-delay error is negligible since the initial amplifier response is much less sensitive to bias with the large series grid resistor removed. If the residual negative signal at the plate of the second stage is objectionable, it may be clipped by a second crystal diode at the grid of the blocking oscillator keying tube.

The output blocking oscillator was found to contribute a range-delay error of +25 yards at 80% duty cycles. This error was independent of range-delay setting and was caused by an excessively long blocking time-constant. In this oscillator circuit, the length of the output pulse depends upon the size of the cathode coupling condenser, so that any reduction in time-constant means a decrease in the size of the cathode resistor. A reduction from 8200 ohms to 5600 ohms was found sufficient to make the range error negligible at duty cycles over 80%. A corresponding decrease in the resistance of the positive bleeder was required to maintain the cathode bias beyond cut-off for servel operation.

Sawtooth-Generator Modification

Improvement of the sawtooth generator is essentially a problem of shortening the discharge time-constants for both the charging condenser and the feedback condenser. A fairly simple mathematical analysis of the circuit may be made by using linear resistances to approximate clamping tubes. The qualitative results of such an analysis, however, may be inferred from an examination of the circuit, and quantitative experimental data were considered more significant than approximate computations where the development of a specific circuit was the aim. Accordingly, no theoretical treatment was undertaken. The results presented are actual performance data of several circuits employing standard miniature tubes.

In the original sawtooth generator of Figure 2, discharge of the two 0.01-mfd charging condensers takes place through the clamping tube V3A and the cathode resistor of the cathode follower V3B in series with the diode V4A. If the plate of the clamping tube fails to return to its normal level before the start of the next charging cycle, the range delay is modified in two ways. In the first place, any initial charge on the condensers at the start of the sawtooth will cause the conducting point of the pick-off diode to be reached sooner, assuming a given charging current. This will cause the range delay to shorten as the duty cycle is increased. In the second place, since the charging current depends upon the initial drop across the 250,000-ohm resistor, it will be reduced by any residual voltage on the charging condensers. This effect will cause the range delay to increase as the duty cycle is raised. It should be noted that the first effect mentioned will still cause error at zero range, although the magnitude depends upon sawtooth amplitude and will be greater at the maximum range setting. However, the charging-current effect produces an error which is strictly a percentage of the delay setting. For sufficiently long range delays, the percentage error would predominate, but this point was not reached at the 100,000-yard maximum of the experimental unit. Thus, considering the effects due to inadequate clamping by V3A alone, increasing PRF will cause negative range-delay errors.

When the cathode of V3B fails to return to its normal level, the discharge of both the charging and the feedback condensers is imcomplete. Consequently, there are two sources of error to be discussed. The effects on the charging condensers is to reduce the amount of integrated feedback provided through the 120,000-ohm coupling resistor during the charging period. When discharge is incomplete at the start of the next charging period, the cathode of V3B will be held by the discharge currents at a point more positive than the normal idling level. Thus the grid of the tube must rise with the sawtooth voltage until the additional tube current replaces the discharge currents before linear cathode follower action can occur. This means that no feedback is applied during the early portion of the sawtooth; and, since the feedback is positive, tending to increase the slope, a decrease in feedback will cause the range delay to increase as the duty cycle is raised.

Where a second clamping tube is connected at the cathode of the cathode follower, the action of the circuit is somewhat different, but the effect of incomplete recovery is substantially the same. When the clamp is released at the beginning of the charging period, the cathode rises quickly to the equilibrium point for the increased cathode load, and feedback action starts immediately. The equilibrium level will be the same regardless of incomplete discharge as long as the clamping tube has carried the cathode to some more negative voltage so that the initial jump occurs. However, even over this range of operation a variation in feedback takes place, since the magnitude of the voltage jump varies with duty cycle. The initial integrated feedback current depends in turn on the size of this voltage step, and thus the feedback is decreased as duty cycle increases. Again, a positive range-delay error is introduced.

In a practical circuit, the discharge of the feedback, or "bootstrap" condenser, rather than the charging condensers, is the most serious problem. Although the amount of charge lost by the feedback condenser during the sawtooth is identical to that gained by the charging condensers, the feedback condenser must be ten, or preferably twenty, times as large. Thus the discharge time-constant is inevitably much longer. Furthermore, since the voltage loss across the condenser during a single cycle of the sawtooth is small, discharge cannot begin until recovery of the charging condensers is nearly complete, and any clamping tubes involved are operating at reduced plate voltage.

The range-delay error caused by incomplete recovery of the feedback condenser is a range-percentage error due to variation of the charging current. The value of charging current which the feedback acts to maintain is that existing when feedback is first applied. Any variation of the initial charge on the feedback condenser will cause this initial current to vary. In the circuit of Figure 2, the initial charge decreases as duty cycle is increased and the recovery time is shortened. This means that the cathode of the feedback cathode follower is held positive with respect to its normal rest position, and feedback action does not start until the grid of the tube has risen with the sawtooth to a corresponding voltage above its starting point. At this time the voltage across the charging resistor has been decreased from its original value by the amount of the sawtooth rise, and the charging current maintained by feedback during the rest of the charging cycle is correspondingly reduced. Thus the range delay for a given pick-off potentiometer setting increases with increasing duty cycle.

The shift of the cathode-follower starting voltage is not limited to the voltage lost by the feedback condenser during one cycle but depends upon establishing equilibrium between the charge lost during the sawtooth rise and that replaced during the recovery period. When the recovery period is shortened, a new equilibrium is established at a lower value of initial voltage across the feedback condenser. This reduced initial drop reduces the charge lost by reducing the sawtooth charging current, as already described. At the same time, the discharge current is increased, and the discharge period is extended over the initial part of the sawtooth until the delayed feedback starts. These effects combine to fix the operating point for the new, higher duty cycle. For the circuit of Figure 2 the range-delay errors due to this source at the maximum range-delay setting are over ten times as great as those caused by incomplete discharge of the sawtooth charging condensers.

In the circuit of Figure 3, the initial voltage step, which occurs when the cathode follower clamping tube is gated, causes feedback to start immediately for moderately high duty cycles. However, this voltage step is included in the voltage drop which determines the sawtooth charging current. And since the size of the step is reduced as the discharge period is shortened, the charging current is reduced, and the same positive range-delay errors appear. At higher duty cycles, the initial voltage across the feedback condenser decreases to the point where no cathode "jump" occurs, and the circuit then behaves as explained for Figure 2.

It is interesting to note that the charge lost by the feedback condenser over the charging cycle of the sawtooth is nearly independent of the range-delay setting. The voltage rise across the charging condenser is effectively limited when the pick-off diode conducts, a fact causing errors due to incomplete discharge of these condensers to be smaller at low range settings. The feedback condenser, however, continues to discharge through the sawtooth charging resistor. Since the time-constant of this combination is ten or twenty times the sawtooth time-constant, the discharge current will decay only a few percent before the end of the 100,000-yard charging period. Thus the charge lost by the feedback condenser will be only slightly smaller than that lost during a full-amplitude sawtooth corresponding to maximum range-delay setting. This means that the error caused by incomplete recovery will be very nearly a fixed percentage of the range delay for operation at a given duty cycle.

The problem of providing low discharge impedances for the precision sawtooth generator is complicated by the requirement that the condensers must be returned to some precise initial condition and held there until the circuit is gated at the beginning of the next charging cycle. Thus the provision of a very low impedance discharge path for a short period of time can produce only a limited decrease in the sensitivity of the circuit to PRF changes. For example, in Figure 2 the clamping tube V3A might have a high-level positive pulse applied to its grid during the discharge period so that the sawtooth condensers are discharged to ground in a very short time. At the end of the pulse, however, the plate of the tube would drift back to the idling voltage determined by the normal plate resistance. The time-constant for this recovery would be the same as that for initial discharge through the same plate resistance. Since the equilibrium voltage is closer to ground than to the maximum sawtooth voltage at which the initial discharge may start, an improvement in recovery time should occur. But the time for complete recovery is still dependent on the idling plate resistance of the clamp. To preserve 0.1% accuracy, the discharge must be complete within 0.1% of the initial charge on the condenser. This requires a period equal to 6.9 RC. Assuming that the recovery exponential, where the condenser is clamped to ground, has an amplitude one-tenth as large as the initial transient, the required discharge time will be reduced to 4.6 RC, excluding the time required for initial clamping. In the case of the feedback cathode follower, however, clamping to ground may actually increase the amplitude of the recovery transient. Since feedback-condenser recovery is the most serious problem, the use of high-level clamping pulses has little advantage, considering the circuit complications involved. Therefore, it was decided to limit experimentation to cases where the clamping current was the normal idling current of the tube involved. Thus, circuits using gas discharge tubes were ruled out, and the experimental work was limited to evaluating the performance of several circuits of varying complication, all employing triodes having positive grid returns as clamps.

The first criterion for a good clamping tube under the stated conditions is high plate current at zero grid bias and low plate voltage. A fairly sharp cut-off is also desirable to make the sawtooth starting time less dependent on the rise time of the gating pulse. These requirements are best fulfilled by a power pentode such as the 6AG7. Beam power tubes such as the 6V6 or miniature 6AQ5 will furnish large clamping currents but require a high bias for plate current cut-off. This is also true of low-mu power triodes. If power tubes are excluded, the best choice for a clamping tube is a medium-mu triode such as the 6SN7 or miniature 12AU7. Since 12AU7's are used for all other triode stages in the original range-delay circuit, their use as clamps is desirable from the standpoint of simplicity. These tubes were therefore employed exclusively in the experimental work, and an attempt was made to devise circuits giving adequate performance with the low clamping currents available from these tubes. The circuits developed proved to be reasonably satisfactory, and no tests were made using power tubes. The gain in clamp performance to be expected from the substitution of a power tube may be determined for any of the circuits presented by comparing tube characteristics. Without additional circuitry, however, the over-all range-delay errors will not be reduced by the same factor as the discharge time-constants, since other factors such as starting time shifts soon become almost as important as condenser discharge.

One scheme that may be used to secure reduced discharge time-constants without high clamping currents lies in return of the clamping tube cathodes to a negative supply with limiting diodes from the plates to ground. Under these conditions, the complete discharge cycle takes place during the fast initial fall of the exponential and may take only a fraction of the time needed for 0.1% recovery at 6.9 RC.

Decrease of circuit capacities is obviously as effective as reduction of discharge impedances in shortening recovery times. It was found possible to reduce the charging condenser values of the original circuit by 50% without any marked loss of stability or linearity. No tests were made to determine just how far this reduction could be carried, but an excessively high impedance level would make stray loading of the precision time-constant more significant, would reduce the current available to drive the output amplifiers, and would make the circuit more susceptible to hum fields and other stray pick-up. Any of the circuits selected for comparison could be made less sensitive to PRF changes by a further increase in charging-circuit impedance, but thorough tests of stability and linearity would have to be made to determine the acceptable maximum.

The feedback-condenser capacity must be made at least ten times the charging capacity for good linearity, a factor of twenty usually being preferable. In the interest of low sensitivity to PRF changes, however, the value should not be made larger than actually needed. Although the charge lost during the sawtooth is independent of capacitance, the larger condenser has a longer discharge time-constant and must be discharged at an unfavorably low clamping-tube plate voltage and after the discharge of the sawtooth charging condensers is more nearly complete. The smaller voltage loss during the sawtooth for the large condenser makes the effect of incomplete discharge less serious. But at high duty cycles, the effect of the longer time-constant predominates, and range-delay shifts are found to be greater when a larger condenser is used.

DETAILS OF MODIFIED CIRCUITS

Improvement of the Single-Clamp Sawtooth Generator

It was found possible to make a considerable improvement in the circuit of Figure 2 without the use of additional tubes. By using only 100 volts of sawtooth amplitude instead of 150 to 200 volts, it was found possible to maintain 0.1% linearity with a cathode-follower load of 5,000 instead of 10,000 ohms. This change reduces the maximum range-delay error from nearly ±2,500 to ±1,000 yards in 100,000 for an 80% duty cycle. A further improvement may be made by increasing the impedance of the sawtooth charging circuit. Linearity and stability will eventually suffer as impedance becomes so high that stray capacitance, leakage resistance, and diode back resistance are significant. There seems to be, however, no serious objection to doubling the impedances shown in Figure 2, increasing the charging resistor to 500,000 ohms, and reducing the two series charging condensers to 0.005 mfd for an effective capacity of 0.0025 mfd. When this charging circuit is used with a 5,000-ohm cathode-follower load, the maximum range error at 80% duty cycle is reduced to ±430 yards. By adding a triode section to the gate multivibrator and a dual diode for coupling as shown in Figure 3, the error may be reduced to ±90 yards in 100,000 at 80% duty cycle. Aside from range-error considerations, the three-tube multivibrator circuit is almost essential for high-duty-cycle operation because of excessive shortening of the gate from the two-tube circuit. If a negative supply of 100 volts or over is available, the triode gate-coupling circuit shown in Figure 4 may be substituted for the dual diode with equally good results. The figure of ±90 yards represents very nearly the minimum error which can be obtained with a single-clamp circuit. Nearly all of the remaining error is due to inadequate feedback condenser discharge, and this problem cannot be solved by lowering the clamping impedance across the charging condensers. Any further improvement would have to be obtained by decreasing the values of the feedback condenser and the cathode-follower load, with an accompanying decrease in sawtooth linearity. If 0.1% accuracy is to be maintained, no appreciable further loss of linearity can be allowed. Additional circuitry is therefore indicated where better accuracy is required.

The stability of the modified circuits will be as good as that of the original circuit. Linearity for a given sawtooth amplitude will suffer as the cathode-follower load is reduced but may be maintained over a limited range of loads by reducing sawtooth amplitude.

Two-Clamp Circuits with Grounded Returns

The complete circuit of Figure 3 represents the next step in reduction of sensitivity to PRF changes. Here, a second clamping tube is added across the cathode-follower load. This tube might have been placed in parallel with the original cathode follower to give more linear feedback for a given cathode load. The best result that could be expected, however, would be a 50% reduction in the ±90-yard figure under the same condition of borderline linearity. By using the additional tube as a clamp, this reduction of error was obtained with any desired cathode-follower load. The exact circuit shown in Figure 3 had a maximum error of ±80 yards at 80% duty cycle. The clamping tube grid return of 120,000 ohms was the best compromise between low clamping resistance and starting time shift due to gate multivibrator loading. A greater reduction in error may be made by using the triode gate-coupling amplifier. For this circuit, a common grid return of 47,000 ohms is the optimum value for the two clamping tubes. The range-delay error is reduced to ±45 yards.

The stability of these circuits to plate and filament-voltage variations is as good or better than that of the original circuit. The sensitivity of the second circuit to the negative gate-amplifier supply is ±15 yards for ±20% variations, a value much lower than the sensitivity to plate and heater supplies

Two-Clamp Circuit with Negative Return

In the circuit of Figure 5 the clamping tubes are returned to a regulated negative supply. A diode, V4B, is used to catch the plate of the

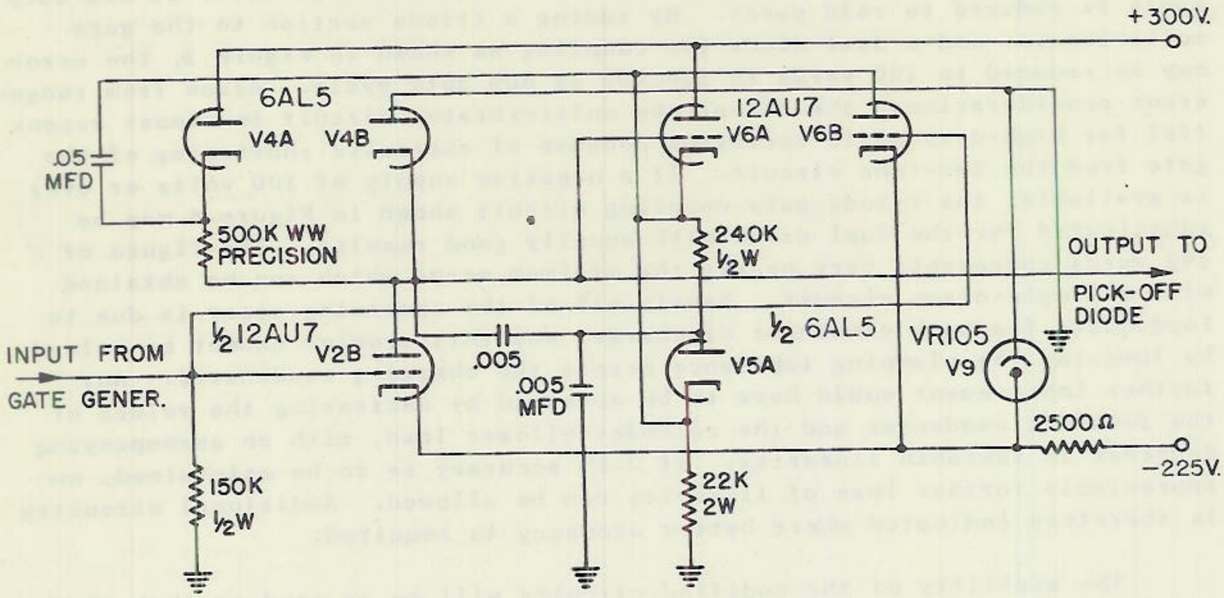

Figure 5- Sawtooth generator with negative clamping

first clamp, V2B, at ground. The low impedance of the cathode follower holds the plate of the second clamp, V6B, slightly above ground. The range-delay error for this circuit was less than ±20 yards in 100,000 at an 80% duty cycle. Much lower clamping-tube grid currents are required here for the same effective discharge impedance. Approximately 0.35 ma per tube is used, as compared to 3.2 ma per tube for the best grounded-clamp circuit. This means a desirable reduction in the loading of the gating-pulse source.

The disadvantages of using a negative clamp supply, aside from the complication, are increased sensitivity to plate and filament-supply voltages and moderate sensitivity to variation of the negative supply to the VR tube. A minor drawback is the fact that the starting voltage of the sawtooth is a few volts below ground instead of above. This means that the range delay cannot, as in other circuits, be reduced to zero by running the pick-off potentiometer to ground.

PERFORMANCE COMPARISONS

Performance data for eight circuit modifications are arranged in the accompanying table. The range-error figures exclude the shift occurring in the output amplifiers and pedestal blocking oscillator. This shift amounts to ±40 yards in 100,000 where the circuit given in Figure 2 is used. The modified circuit of Figure 3 contributes negligible error.

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COMPARISON OF VARIOUS CIRCUIT MODIFICATIONS

Circuit†	Range Error Caused by PRF Changes (Yards)*	Duty Cycle for a Max. Error of ±50 Yd	Range Error Caused by ± 1% Voltage Variations			Additional Parts Needed for Modification✱
			Heater (yd)	Plate (yd)	Neg. Supply (yd)	
A	± 2,500	35%	∓12	± 40	--	None
B	± 1,000	35%	∓12	± 40	--	None
C	± 430	40%	∓12	± 40	--	None
D	± 90	77%	∓12	± 40	--	1. Triode 2. Diodes 3. Resistors
E	± 230	75%	∓12	± 40	--	Same as D
F	± 80	77%	∓11	± 10	--	2 Triodes 2 Diodes 3 Resistors
G	± 50	80%	∓11	± 10	∓ 0.75	3 Triodes 2 Resistors
H	± 20	--	∓25	± 55	∓ 3.2	2 Triodes 3 Diodes 1 VR Tube 4 Resistors

* For a maximum range delay of 100,000 yards.

✱ In the modification of the output amplifiers, one resistor was eliminated and two crystal diodes added. All triodes used are sections of miniature dual triodes (12AU7's) and diodes are sections of dual diodes (6AL5).

† CIRCUIT DETAILS:

Circuit A The original circuit as given in Figure 2.

B The same circuit as A except for a reduction in cathode-follower load from 10,000 to 5,000 ohms.

C The same circuit as B, with charging condensers decreased from 0.01 to 0.005 mfd and the charging resistor increased to 500,000 ohms.

D The circuit of modification C with the three-tube gating multivibrator and diode-coupling circuit of Figure 3 substituted for the corresponding circuits of Figure 2.

E The circuit D with the cathode-follower load increased from 5,000 to 10,000 ohms for better feedback linearity.

F The complete circuit of Figure 3.

G The circuit of Figure 3 with the triode gate-coupling amplifier shown in Figure 4 substituted for the diode coupling circuit.

H The circuit of Figure 3 with negative clamp returns as shown in Figure 5.

The errors tabulated for PRF variation are those for the least favorable combination of range-delay setting and PRF over the range of 100,000 yards and 25% to 80% duty cycle. PRF effects below 25% are extremely small. Errors due to supply voltage variations are substantially linear functions over at least a ±10% range of variation.

ACKNOWLEDGMENT

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