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Tenth (Final) Technical Report
of the
Navy Research Project,
N 7 onr - 28808

SPEED OF TRIGGERING OF THE ECCLES-JORDAN CIRCUIT

by

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Foreword

Although this is the final report of Navy Research Project N7 onr - 28808, it does not represent a summary of the work done or the results obtained under this project. Rather, it is a continuation of the seventh and eight reports, and should be read in conjunction with these reports.

Much of the analysis presented in this report is not new. As a summary of known facts, however, it may be of value in the design of trigger circuits. Application of the method of analysis of Technical Report No. Eight in the determination of the figure of merit for high-speed triggering is believed to be new.

When the triggering voltage applied to Eccles-Jordan circuit is equal to or slightly larger than the minimum value required to initiate change of equilibrium state, or if the triggering amplitude is considerably greater than the minimum value but rises very slowly, the change of state is a regenerative process involving both tubes. On the other hand by the use of a negative triggering voltage of short rise time, high amplitude, and long duration applied to the grid of the initially conducting tube, it is possible to trigger the circuit in such a manner that the initially conducting tube is suddenly cut off and remains so throughout the change of equilibrium state. The voltage across the load resistor of the initially conducting tube is then a step function and the transfer process is a transient that does not involve the initially conducting tube. A similar situation obtains when a positive triggering voltage of short rise time, high amplitude, and long duration is applied to the grid of the tube that is initially nonconducting.

An analysis by Snowdon for the type of transition in which both tubes participate indicates that a rapid triggering requires a high ratio of transconductance to effective tube input capacitance.[1] This same result is obtained by the method of analysis discussed in the Eighth Technical Report of this project, in which the Eccles-Jordan circuit is considered as a feedback amplifier. Figure 1 shows the Eccles-Jordan circuit, and Fig. 2 shows the two-stage direct-coupled amplifier from which it is derived by connecting the output terminals to the input terminals. The curve of Fig. 3 shows the general manner in which the output voltage e_o varies with the input voltage e_i, and possible equilibrium values of voltage are those corresponding to the intersection of the curve with the straight line, $e_o = e_i$.

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[1] Snowdon, S. C., Ph. D. thesis, Cal. Inst. of Tech., 1945. See Radiation Laboratory Series, Vol. 19, Sec. 5.7 for an abstract.

As pointed out in the eighth technical report, the dynamic curve corresponding to rapidly changing voltages is less steep than the static curve, the steepness decreasing with increase of rate of change of voltage. For a sufficiently high rate of change of voltage, the amplification of the circuit of Fig. 2 is unity, and the slope of the dynamic curve is the same as that of the straight line, $e_o = e_i$. If this is so, transfer from one state of equilibrium to the other can take place without violating the requirement that $e_o = e_i$, the rate of change of voltage at each instant during the transfer necessarily adjusting itself so that the overall amplification is unity and the slope of dynamic curve is also unity.

Because the reduction in slope of the dynamic characteristic is the result of shunt capacitances, and because the initial slope is the low-frequency amplification of the amplifier, the value of de_i/dt at which the slope (amplification) is reduced to unity increases with increase of low-frequency amplification and with decrease of shunt capacitances. The value of R_b used in trigger circuits is usually small in comparison with the plate resistance of the tube and $R_c + R_c'$ is usually much larger than R_b. Consequently the low-frequency voltage amplification is to a first approximation equal to $g_m R_b$ and the figure of merit of the circuit for rapid triggering is $g_m R_b / C_e$, where C_e is the total effective shunt capacitance of the tube. It should be noted that the increase of de_i/dt resulting from an increase of R_b does not necessarily reduce the time required for triggering, since total change of e_i between the two states of equilibrium also increases with R_b.

When the triggering voltage has an amplitude considerably greater than the minimum value that causes the circuit to trigger and when it rises in a time short in comparison with the triggering time, the behavior of the circuit depends upon a number of factors, including the magnitude of the voltage, its rise time, and its duration. One practical case that yields to analysis is that in which the magnitude of the triggering voltage rises very rapidly to a value sufficient to cut off the initially conducting tube or to raise the grid voltage of the initially nonconducting tube to zero, and in which the duration of the triggering voltage exceeds the time required for equilibrium to be established in all parts of the circuit. If the plate current of the tube to which the control pulse is applied is assumed to change instantaneously from its "on" value to zero, or vice versa, and not to change thereafter, the remainder of the triggering process is a transient phenomenon in which this tube does not participate.

If tube 1 is initially conducting and the triggering voltage cuts this tube off, application of the triggering voltage is followed by a transient period in which both tubes are cut off and charging or discharging of the circuit capacitances through the circuit resistances results in an exponential rise of grid voltage of tube 2. During this portion of the transient, the input capacitance of tube 2 is merely the "cold" capacitance. When the grid voltage of tube 2 reaches the cutoff value, plate current starts flowing in this tube and its plate voltage falls in a manner determined both by the rise of grid voltage and by the capacitances and resistances in its plate circuit. During this portion of the transient, the input capacitance of tube 2 is augmented as the result of the Miller effect, and the rate of rise of grid voltage is consequently decreased. (Because of the high rate of change of grid voltage, however, the amplification of tube 2 is relatively low and the Miller effect is much smaller than it would be if the same circuit were used as a low-frequency amplifier. When the grid voltage of tube 2 reaches the value at which grid conduction starts, voltage drop through the coupling resistor R_c prevents appreciable further rise of voltage. During the remainder of the transient, the plate voltage of tube 1 continues to rise exponentially as its plate-cathode capacitance charges, and the plate voltage of tube 2 falls exponentially as its plate-cathode capacitance discharges. The equivalent circuit for this type of triggering is shown in Fig. 4. Opening of switch S_1 represents the cutting off of tube 1 by the impressed triggering pulse. Closing of switch S_2 represents the starting of plate current in tube 2, and the closing of S_3 represents the initiation of grid conduction in tube 2.

A similar series of transients takes place if tube 1 is initially nonconducting and a large positive pulse is applied to the grid of that tube.

Although the circuit of Fig. 4 is rather involved, simplifying assumptions make the circuit amenable to solution. Furthermore, the manner in which the various circuit elements affect the speed of transition can be seen by inspection.

The foregoing analyses indicate that the speed of triggering may be increased in the following ways:

(1) By decreasing tube and circuit capacitances. Although the Miller effect causes grid-plate capacitance to be more objectionable than grid-cathode and plate-cathode capacitance, this factor is probably of considerably less improtance than in amplifiers.

(2) When the circuit is triggered in such a manner that only one tube participates in the switching transient, the speed of triggering may be increased by decreasing the load and coupling resistances in order to reduce the RC time constants. When both tubes participate in the entire transfer process, increse of load resistance increases the low-frequency amplification and therefore the rate of change of voltage. On the other hand, it increases the total change of voltage between states. It seems likely that there is an optimum value at which the time of transfer has a minimum value.

(3) By increasing the tube transconductance. When the circuit is triggered in such a manner that both tubes participate in the entire transfer process, increase of transconductance increases the low-frequency amplification and therefore the rate of change of voltage at which the amplification is reduced to unity. When the circuit is triggered in such a manner that only one tube participates in the transfer process, high transconductance favors rapid charging of the effective load capacitance during the portion of the transfer transient in which the tube conducts. Increase of transconductance also reduces the minimum values of circuit resistances for which the circuit has two stable states. It therefore makes possible the use of smaller resistances and therefore more rapid charge and discharge of the circuit capacitances during the transfer transients.

(4) When the circuit is triggered by means of a long large-amplitude negative pulse applied to the grid of the initially conducting tube, the speed of transfer is increased by an increase of positive grid supply voltage. The reason for this is that the maximum voltage to which the input capacitance of the initially non-conducting tube is charged is limited to approximately zero by voltage drop caused by the flow of grid current through the coupling resistor. The higher the impressed voltage in the grid circuit, the lower is the percentage of the final voltage to which the capacitor charges and hence the shorter the charging time.

(5) The transfer time can be decreased by reducing the range through which the plate and grid voltages change. As pointed out under (2), if this is done by reducing the resistances R_b, the reduction of low-frequency amplification reduces the rate of change of voltage and the net effect may not be to decrease the transfer time. Furthermore, decrease of R_b reduces the stability of the circuit in the two states of equilibrium and therefore makes it more critical of adjustment and more susceptible to undesired triggering by fluctuations of supply voltage or noise.

A more satisfactory method of reducing the voltage change is to use clamping (catching) diodes that limit the maximum and minimum values of triode plate voltage, as shown in Fig. 5. When the voltage of either of the plates exceeds the voltage V_1, conduction of one of the upper diodes produces a large voltage drop in R_b that prevents appreciable further increase of plate voltage. Similarly, if the voltage of either of the plates falls below V_2, conduction of one of the lower diodes prevents further decrease of plate voltage. The plate voltage change during transition is therefore limited to approximately the difference between V_2 and V_1. An objection to clamping the minimum plate voltage is the effect of the relatively high cathode-heater capacitance of the lower diodes, which augments the plate-cathode capacitance of the triodes. Although crystal diodes may be used, the dependence of their characteristics upon temperature leads to other difficulties in some applications of the circuit. It may then be desirable to clamp only the upper limit of plate-voltage excursion. When clamping diodes are used, the plate load resistors may be made large enough to assure adequate stability and low-frequency amplification.

Comparison of the mechanisms of triggering when both tubes participate in the transfer and when only one tube participates would appear to indicate that the speed of triggering should be greater when both tubes participate. It had been hoped that an oscillographic study of these two types of triggering would yield experimental confirmation of this conclusion, and an extension, without funds, of Contract N 7 onr - 28808 was therefore requested and granted. Unfortunately, the lack of availability of personnel greatly limited the effort that could be put into this phase of the contract, and conclusive results have not yet been achieved. It is the hope of the writer to continue this work and to submit a supplementary report at a later date.

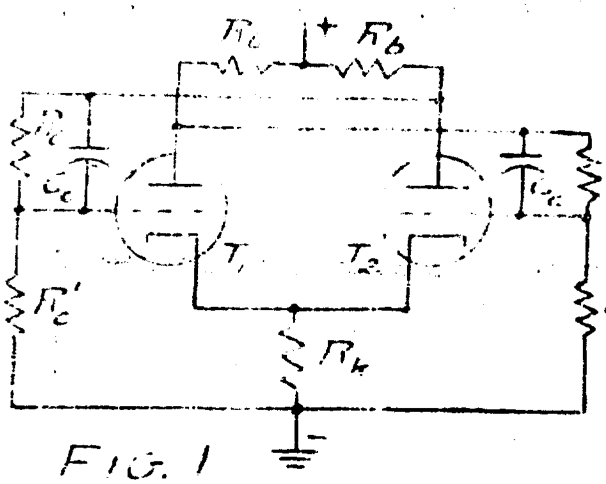

FIG. 1

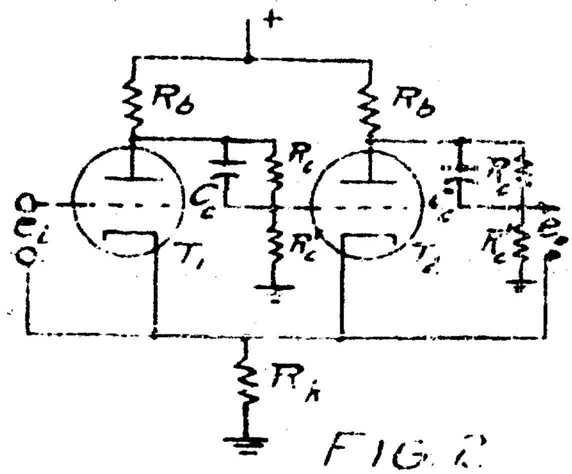

FIG. 2

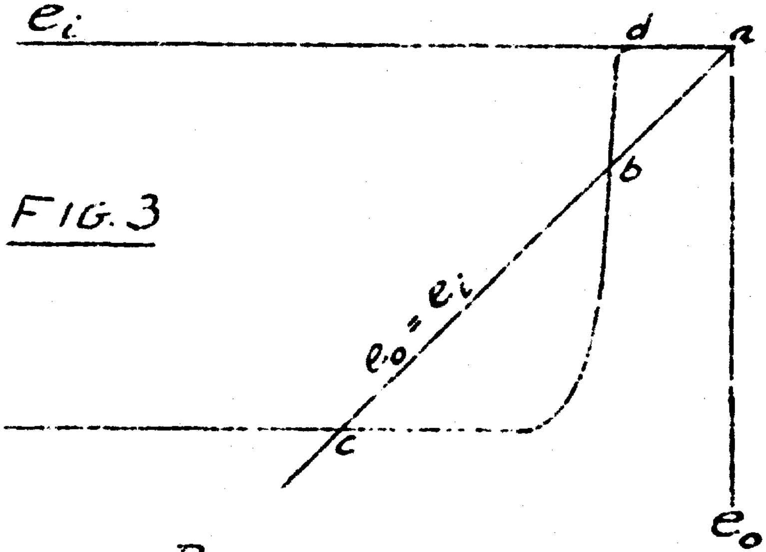

FIG. 3

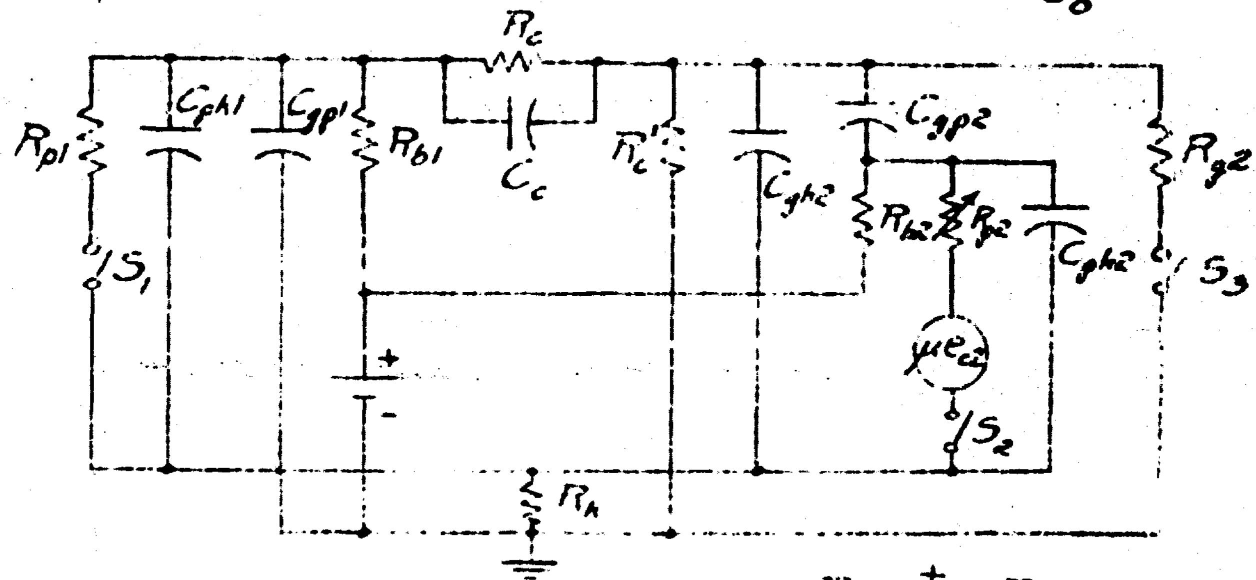

FIG. 3

FIG. 4 →