THE AMPLIFICATION OF SMALL DIRECT CURRENTS

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Abstract

A new type of thermionic tube recently described by Metcalf and Thompson has made it possible for the first time to construct d.c. amplifying circuits with a current sensitivity exceeding that of any form of electrometer except the Hoffman; and with a ruggedness and dependability unattainable with any form of sensitive electrometer. The circuits are easily constructed and simple to operate. Three types of circuits have been tested out and are described. (1) A simple single-tube circuit with a Type R galvanometer has been found satisfactory for measurements of currents as small as 10^{-14} amp. (2) A two-tube bridge circuit gives greater stability and will easily measure currents of 10^{-16} amp. It has been found capable of detecting currents of 5×10^{-18} amp. (3) A two-stage circuit, using one of the new tubes and one of the UX-112A type, will amplify currents of 10^{-14} amp to such a value that they may be read on a microammeter.

Introduction

There is considerable interest among physicists in the possibility of using thermionic tubes for the amplification of very small direct currents, such as photo-currents, ionization currents, and currents due to electron or positive ion beams of various sorts. A number of different circuits have been described in the literature[1] by means of which ordinary radio tubes or screen grid tubes may be employed for this purpose; and while a number of observers have had considerable success in their use, for the most part the electrometer is still the instrument universally employed for measurements of this type.

The difficulties encountered in d.c. amplification are due largely to the fact that practically all thermionic tubes now available have been designed for amplification of rapidly varying currents, and possess characteristics which make them unsuitable for d.c. work. Only a few attempts have been made to design a tube particularly adapted to amplifying direct currents smaller than about 10^{-11} amp. However, very recently Metcalf and Thompson of the General Electric Laboratories have described[2] a new form of tube (the "FP-54 pliotron") particularly designed for this purpose and which is capable of amplifying currents as small as 10^{-17} amp. With this type of tube it is possible for the first time to construct an amplifying circuit with a sensitivity equaling or exceeding that of the best Compton electrometers, and at the same time possessing a ruggedness and dependability unattainable with these instruments. The present paper is an account of some further experi-

[1] See especially, Bennett, Rev. Sci. Inst. **1**, 466 (1930); Dearle and Matheson, Rev. Sci. Inst. **1**, 215 (1930); Razek and Mulder, J.O.S.A. and R.S.I. **18**, 460 (1929); Nelson, Rev. Sci. Inst. **1**, 281 (1930); also refs. 4 and 5 below.

[2] Metcalf and Thompson, Phys. Rev. **36**, 1489 (1930).

ments which have been made with these tubes to investigate their possibilities and limitations under actual working conditions, and to study the circuits in which they can be most efficiently used. An attempt has been made to present the results in a rather detailed and elementary way, so that physicists unfamiliar with vacuum tube technique may be aided in building workable amplifier circuits. The experiments were carried out at the General Electric Research Laboratories during the past summer, at the suggestion and under the direction of Dr. A. W. Hull, to whom the author is very greatly indebted.

It may be well to recall some of the requirements which must be met by circuits to be used for d.c. amplification.[3] Suppose, for example, that it is desired to amplify a current from, say, a photoelectric cell, using a standard

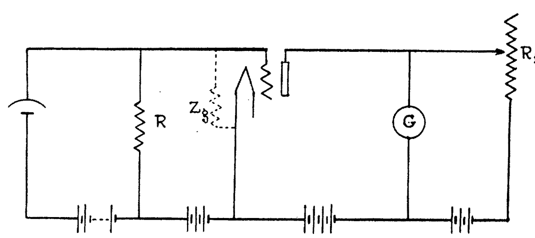

Fig. 1. Simple circuit for d.c. amplification.

circuit such as is represented in Fig. 1. With the photo-cell dark let the resistance R_1 be adjusted so that the galvanometer reads zero. If the photo-cell is then illuminated, the photoelectric current will cause a drop in potential across the grid resistance R, and this will be impressed on the grid of the vacuum tube. The resulting change in plate current will cause a deflection d of the galvanometer, given by

$$d/\sigma = i_G = \Delta i_p = g_m \Delta e_g$$

where σ is the sensitivity of the galvanometer (in mm/amp), $g_m = di_p/de_g$, the mutual conductance of the tube, and Δi_p and Δe_g the changes in plate current and grid potential, respectively. (It is assumed in setting $i_G = \Delta i_p$ that the resistance R_1 is considerably larger than the galvanometer resistance,[3] a condition always satisfied in practice). The voltage sensitivity S_v of the circuit, in mm/volt, then will be,

$$S_v = d/\Delta e_g = g_m \sigma. \quad (1)$$

To attain a high sensitivity to *voltage*, one would choose a tube of high mutual conductance and use it with a sensitive galvanometer. For our present purpose, however, we are more interested in the sensitivity to *current*, since the voltage applied to the grid may be made as large as we please, within limits, by simply increasing R. Since then, $\Delta e_g = Ri$, we have for the current sensitivity, S_i, (in mm/amp),

$$S_i = d/i = g_m R \sigma = S_v R. \quad (2)$$

[3] For a more detailed discussion see Nottingham, Jour. Frank Inst. **209**, 287 (1930).

Therefore, to attain a high *current* sensitivity it is necessary to use also a high value of R. This is the point at which circuits using ordinary radio tubes are severely limited. For it will be seen that the external resistance R is shunted by the grid resistance Z_g of the tube itself, and hence the total resistance cannot be made larger than Z_g. Now in ordinary tubes Z_g is not greater than a few hundred megohms, due to insulation leakage in the tube, to the collection of positive ions by the grid, and other causes. The first requirement, therefore, of a tube used to amplify very small currents is that the input resistance be very high, or what amounts to the same thing, that the grid currents in the tube under normal operating conditions be very small. In the new tube developed by Metcalf and Thompson all sources of grid current have been systematically eliminated or greatly reduced, so that the residual currents are of the order of 10^{-15} amp and the input resistance of the order of 10^{16} ohms. These tubes are therefore capable of giving enormously greater current sensitivity than has heretofore been possible.

In addition, since the tubes operate at a plate potential of only 6 volts, it is feasible to use large capacity storage batteries for a voltage supply, thus greatly reducing galvanometer fluctuations due to changes in battery voltages. The increased steadiness makes it possible to use a more sensitive galvanometer and thus makes up for the fact that the mutual conductance is somewhat lower than in ordinary tubes.

The FP-54 pliotrons are four-element tubes with two grids interposed between filament and plate. The inner grid serves as a space charge grid and the outer grid as a control grid. The normal operating conditions are:

Filament voltage	2.5 volts
Filament current	0.11 amps
Space charge grid	+4.0 volts
Control grid	−4.0 volts
Plate	+6.0 volts

Under these conditions the tubes have the following average characteristics:

Grid input resistance	10^{16} ohms (approx.)
Control grid current	10^{-15} amp (approx.)
Mutual conductance	25 microamp/volt
Plate current	40 microamp
Plate resistance	40,000 ohms
Voltage amplification factor	1
Grid capacity	3 $\mu\mu$F.

Circuits for Use with FP-54 Pliotrons

It is not necessary to develop new types of circuits for use with the new tubes, for it has been found that standard circuits are quite adequate. For a given current sensitivity, of course, a much simpler type of circuit can be used than would be necessary with ordinary tubes. An excellent summary of the theory and practice of d.c. amplification, using ordinary tubes, has been given by Nottingham,[3] and all of the circuits used in this investigation have been described in detail in his paper. Slight modifications are necessary, due to the fact that the FP-54 is a four-element tube.

1. *The single-tube circuit.* A very simple type of circuit which has been found suitable for many ordinary current measurements is shown in Fig. 2. It is a standard type of single-stage d.c. amplifier, in which the plate current

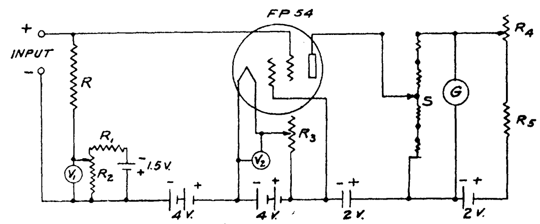

Fig. 2. Single tube circuit using FP-54 Pliotron. R, high resistance, 10^7-10^{11} ohms: R_1, fixed resistance, 100 ohms: R_2, 400 ohm potentiometer: R_3, 20 ohm rheostat: R_4, 10,000 ohm rheostat: R_5, fixed resistance, 40,000 ohms: V_1, 0–200 millivoltmeter: V_2, 0–5 voltmeter; S, Ayrton shunt.

is balanced out of the galvanometer by means of an auxiliary battery and rheostat. The numerical values of the various resistances used are given in the figure for convenience, though these are not at all critical, and will vary for different tubes.

The method of operation is as follows: With the tube operating at normal voltages the galvanometer is made to read zero by adjustment of the rheostat R_4. The voltage sensitivity of the circuit is then determined by applying to the control grid a series of known voltages by means of the potential divider, R_2, and observing the corresponding galvanometer deflections. If the deflection is then measured for an unknown input current i, the magnitude of i can at once be determined if R is known. There is a linear relation between galvanometer deflection and input voltage as long as the latter does not exceed about 300 millivolts, in spite of the fact that the tubes do not operate normally on the straight part of their characteristic.

The circuit may be made independent of the tube characteristics by using a null method, in which the galvanometer deflection due to the input current is brought back to zero by applying a compensating voltage e by means of R_2. The input current is then simply equal to e/R. The *accuracy* then attainable is limited only by the accuracy of the voltmeter V_1, the accuracy with which R is known, and the precision with which the galvanometer can be set to zero.

The highest voltage sensitivity which can be attained with such a circuit is limited by the fluctuations due to changes in battery voltages and other causes. By using large storage batteries (e.g. 90 amp–hr) for the voltage supply and by careful shielding it has been found possible, with a Leeds and Northrup Type R galvanometer, ($1/\sigma = 5\times 10^{-10}$ amp/mm), to obtain a stable voltage sensitivity in excess of 50,000 mm/volt. With a resistance R of 10^{10} ohms, a current sensitivity ($=1/S_i$) of 2×10^{-15} amp/mm is attained. Accurate measurements (to better than 1 percent) can then be made of currents of 10^{-13} amp or larger. This is just about the order of magnitude of the currents usually measured in electrometer circuits.

A somewhat higher current sensitivity may be obtained by "floating" the control grid, i.e., by making R infinite. The residual grid currents within the tube will then cause the grid to charge up slowly, and a steady drift of the galvanometer is observed. The rate of change of grid voltage will be i_g/C, where i_g is the grid current and C is the electrostatic capacity of the grid circuit. For the FP-54 tubes the grid current is in the neighborhood of 10^{-15} amp and the capacity of the grid itself is about $3\mu\mu$F. If the remainder of the grid circuit be assumed to have a capacity of 10 $\mu\mu$F, and if the voltage sensitivity, S_v, is 10^5 mm/volt, then the rate of drift of the galvanometer will be approximately 7.7 mm/sec. This drift is normally very constant, so that an input current as small as 10^{-16} amp can be measured by noting the *change* in the rate of drift which it causes. This is the method used in the General Electric Laboratories for measuring the grid currents in the tubes as they come from the factory.

2. *Balanced tube circuit.* It was found that, when currents of 10^{-14} amp or less are to be measured, more satisfactory operation is obtained with a two-tube circuit of the type developed by Wold, Wynn-Williams[4] and Eglin.[5] This method is also more satisfactory for measurement of larger currents where great steadiness and precision are desired. A diagram of the circuit actually used is shown in Fig. 3. It will be noted that it is essentially a Wheat-

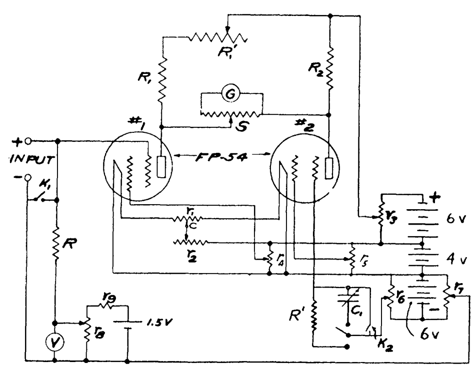

Fig. 3. Two-tube bridge circuit. R, R', high resistances: R_1, fixed resistance, 5000 ohms: R_2, fixed resistance, 10,000 ohms: R_1', resistance box, 10,000 ohms: r_1, 2 ohm rheostat: r_2, 20 ohm rheostat: r_3 to r_8, 400 ohm potentiometers: r_9, fixed resistance, 1000 ohms: K_1, K_2, electrometer keys: V, millivoltmeter: S, Ayrton shunt: C_1, variable air condenser, $15\mu\mu$F.

stone bridge, with amplifier tubes in two of the arms and resistances in the other two. When this circuit is properly balanced it can be shown[3] that the galvanometer will be unaffected by fluctuations in the battery voltages. A considerably greater steadiness is thereby attained, so that a galvanometer of higher sensitivity may be used and a higher stable voltage sensitivity obtained. It was found, in fact, that satisfactory operation could be maintained

[4] Wold, U. S. Patent 1232879 (1916). Wynn-Williams, Proc. Camb. Phil. Soc. **23**, 810 (1927); Phil. Mag. **6**, 324 (1928).

[5] Eglin, Jour. Opt. Soc. **18**, 393 (1929).

at a sensitivity of 250,000 mm/volt, using a galvanometer sensitivity of $1/\sigma = 5 \times 10^{-11}$ amp/mm.

The method of balancing is as follows:[3] With the tubes operating at normal voltages, R_1' is adjusted to bring the galvanometer to zero. By means of r_3 a small change is then made in the plate voltage and the effect on the galvanometer noted. R_1' is then changed by, say, 1000 ohms and the galvanometer brought back to zero by adjustment of the various grid potentials. The plate potential is again changed by the same amount as before, and if the resulting galvanometer deflection is smaller, R_1' has been altered in the right direction. The process is then repeated until a change in plate potential produces no effect on the galvanometer.

In a similar manner the effect of filament voltage changes is observed by varying r_2, and a position of the contact C on r_1 is found such that small variations in r_2 produce no effect on the galvanometer. During this adjustment R_1' is left fixed and the balance restored after each change of C by manipulation of the grid potentials. The circuit is now ready for operation, and may be calibrated in the same way as the single-tube circuit.

The circuit shown in Fig. 3 was designed so that it could be used either with the steady deflection method or the rate of drift method. If only the steady deflection method is to be used the condenser C_1 may be eliminated and if only the rate of drift method is to be used, the resistances R and R' may be eliminated. In either case the operation is similar to that of the single-tube circuit, tube No. 1 being the active tube and No. 2 acting merely as a "dummy." The resistance R' in the grid circuit of the second tube makes for greater symmetry and hence increases the stability somewhat, but in many cases it may be left out and the grid connected directly to r_6. If R is 10^{10} ohms and the voltage sensitivity 250,000 mm/volt, the current sensitivity, $1/\sigma$, will be 4×10^{-16} amp/mm. Still higher resistances may of course be used.

An exceedingly high sensitivity may be obtained with this circuit using the rate of drift method of measurement. If the grids of both tubes are floated, and if they both charge at the same rate, then there will be no effect on the galvanometer. In general, however, the grid currents of two tubes will not be the same, but the rate of charge of the two may be *made* the same by increasing the capacity of one grid. This was accomplished by introducing the variable $15\mu\mu$F condenser[6] C_1 in the grid circuit of the second tube. The tube with the largest grid current was made No. 2 in the circuit. This condenser was then adjusted until the galvanometer showed no drift. If a current i is now started in the input circuit, this will change the rate of charge of the grid of the first tube and hence give a galvanometer drift which is proportional to i.

The smallest current which can be detected by this method is limited only by the fluctuations of the circuit. The effects of external electric and magnetic fields, especially rapidly varying fields, were carefully eliminated by enclosing the entire circuit in a metal container which was almost air tight. All

[6] A satisfactory condenser was made by taking an ordinary radio condenser and replacing the bakelite insulation by quartz.

rheostats and connections should of course make positive contact; the storage batteries must be in good condition; to prevent insulation leaks the tubes must be kept dry. It was even found necessary to eliminate effects due to residual ionization of the air by enclosing the control grid leads in small quartz tubes painted on the outside with a suspension of graphite ("aquadag"). A wide band of aquadag was also painted around the tubes themselves to serve as a guard ring. When all these precautions were taken, it was found that the residual fluctuations were sufficiently small that an input current of approximately 5×10^{-18} amp could be detected and measured. Such a current produced a galvanometer drift in the circuit used of about 10 mm/min, and the fluctuations were also of this order. These fluctuations were of the order of magnitude to be expected from shot-effect fluctuations in the control grid currents in the two tubes, and hence the limit of sensitivity of the tubes was approximately attained.

It is of interest to note that a current of 5×10^{-18} amp is only 30 electrons per second, and the shot-effect fluctuations in such a current over a period of one second are of the order of 15 percent. If tubes could be constructed in which the grid currents were as low as 10^{-17} amp (and this may not be impossible) the sensitivity limit of the amplifier could be pushed to 5×10^{-19} amp, or 3 electrons per second. If a short period galvanometer were used, individual electron pulses could be observed.

It will be noted that the maximum voltage sensitivity attainable with this circuit is about five times that attainable with the Compton electrometer, and is 25 to 50 times greater than the usual operating sensitivity of the electrometer. There is an even greater difference between the current sensitivities of the two instruments, due to the smaller capacity of the amplifier. The author has found that, roughly speaking, a well-built amplifier is as stable at a sensitivity of 100,000 mm/volt as a good Compton electrometer at 5,000 mm/volt. In addition the amplifier has the advantages of greater mechanical ruggedness and short period. Furthermore, the sensitivity of the amplifier circuit has been found to remain constant over long periods of time, in contrast to the frequent adjustments of quadrant and needle required to maintain a constant high sensitivity of an electrometer. In short the amplifying circuit herein described has been found to be a practical and convenient current-measuring device,[7] with an attainable sensitivity greater than that of any known instrument, with the exception of the Hoffman electrometer and the Geiger counter.

3. *The two-stage amplifier*. For many problems it is desirable to measure very small currents, such as photoelectric currents, but at the same time to use an extremely rugged meter.[8] In order to test out the possibility of using instruments still more rugged than the Type R galvanometer, a two-stage

[7] Such a circuit is now being used successfully by Professor G. E. M. Jauncey and Mr. W. D. Claus at Washington University for measurements of ionization currents in an x-ray spectrometer.

[8] This is true, for example, in the photoelectric photometry of stars, where the measuring Instrument must be mounted directly on the telescope.

amplifier circuit shown in Fig. 4 was constructed. By employing a UX-112A tube in the second stage it is possible to measure the output with an ordinary microammeter (0–100 μ amp). A second state of amplification could of course be employed with either of the two circuits previously described. It seemed, however, that the greatest simplicity and convenience could be attained by using in the first stage a balanced circuit in which the dummy tube is replaced by a variable resistance. In place of the galvanometer, the second stage of amplification is substituted.

It is evident that the requirements for the tube to be used in the second stage are quite different from those for the first stage. For, while the chief requirement for the first stage is a high grid resistance, this is not at all necessary in the second stage, since the resistances R_1 and R_2 are relatively small. One will therefore use in the second stage a tube of high mutual conductance.

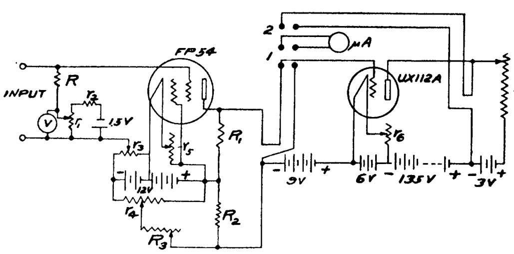

Fig. 4. Two-stage amplifier. R_1, R_2, Fixed resistances, 10,000 ohms: R_3, variable resistance, 20,000 ohms: r_1, r_3, r_4, 400 ohm potentiometers: r_2, fixed resistance, 1000 ohms: r_5, 60 ohm rheostat: r_6, 6 ohm rheostat: r_7, rheostat with fine adjustment, 1000 ohms: R, high resistance, 10^7–10^{11} ohms.

If a voltage e is applied to the grid of the first tube, then the change in the voltage of the grid of the second tube will be ke, where k stands for the expression

$$\mu R_p/(R_p + r_p).$$

Here μ is the voltage amplification factor of the first tube, R_p the external resistance in the plate circuit, and r_p the internal impedance of the first tube. The change in the plate current of the second tube will then be

$$\Delta i_p = g_{m2}ke$$

where g_{m2} is the mutual conductance of the second tube. This change in plate current will be read on the microammeter. Now the voltage amplification obtained by the FP-54 in the circuit shown is actually less than 1, so that if another FP-54 were used in the second stage, the overall sensitivity of the combination would be less than for a single tube. However, if a tube of large mutual conductance is used in the second stage, an increase in sensitivity is obtained. With the circuit shown in Fig. 4 the over-all sensitivity was found to be approximately 375 microamp/volt. Using an input resistance, R, of 10^{11} ohms, an output current of 1 microamp was obtained for an input current of 2.7×10^{-14} amp. This is a current amplification of 3.75×10^7.

The method of operating the circuit is as follows: With the double-pole-double-throw switch in position 1, the microammeter reads the output of the first stage only. The first stage is then balanced until the meter reads zero. The balance is obtained in a manner similar to the balance of the two-tube circuit by adjustment of R_3 and r_4. The microammeter switch is then thrown to position 2 and r_5 adjusted until the meter again reads zero. The circuit is then ready for operation.

The usefulness of such a circuit is quite apparent for problems in which ruggedness, portability or economy are of importance. A very inexpensive microammeter may be used since it serves only as an indicating instrument, and will be calibrated in terms of input voltage by means of the potentiometer r_1 and voltmeter V.

As a test of the practical use of this circuit the input terminals were connected to a G.E. caesium photoelectric cell, type UX-867, illuminated by a small headlight lamp. An output current of several microamperes was observed when the lamp filament was at a temperature such that it was scarcely visible to the eye in a dimly lighted room.

There are many variations and improvements on the two-stage circuit which at once suggest themselves. The circuit shown in Fig. 4 was chosen primarily for its simplicity, and it is described here because it was found to give quite satisfactory operation. Its stability and sensitivity could undoubtedly be improved by using a complete two-tube bridge circuit in each stage, using two FP-54 tubes in the first and two UX-112A tubes in the second stage.

4. *General precautions.* The chief purpose of the present paper is to bring out the fact that with the new FP-54 pliotrons the construction of a highly sensitive d.c. amplifier has been made a relatively simple task. It may be well to remark, however, that *regardless of the instrument used to measure or detect small currents*, the circuits which carry them must always be insulated and shielded with the greatest care. The problem of shielding is of even greater importance for an amplifier circuit than for an electrometer. This is due to the fact that an electrometer is practically insensitive to high frequency electric fields of constant intensity, while the amplifier actually serves as a detector for such fields. Air-tight shielding of the grid circuits is therefore essential if the amplifier is to be used in the vicinity of high voltage equipment (e.g., x-ray tubes). Shielding of *all parts* of the amplifier circuit is advised.

In all other respects (such as choice of insulation material, construction of grounding keys and high resistances, etc.) the grid circuits of an amplifier may be treated exactly as an electrometer circuit of equal sensitivity. It has been found necessary to operate the tubes at their rated voltages for from half an hour to two hours before readings are begun, in order that temperature equilibrium be obtained and that the electrostatic charges on the walls of the tubes and other places shall have reached a steady state.