An Improved d.c. Amplifying Circuit

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The sensitivity of d.c. amplifying circuits with FP-54 tubes is limited by the stability which can be obtained. In single-tube circuits it is necessary to balance out fluctuations caused by changes in battery e.m.f. and in filament emission. Soller's circuit for balancing out e.m.f. changes has been studied in detail and a modified circuit has been developed in which the adjustments are less critical and which allows balancing out of changes in filament emission also. The latter is accomplished by balancing the plate current against the current to the space-charge grid. Details of construction and manipulation of the new circuit are given, as well as data on its stability.

INTRODUCTION

THE highest sensitivity which is attainable with a d.c. amplifier, with FP-54 tubes, is usually determined by the stability which can be achieved. Attaining high stability involves the elimination of slow drifts and also of random fluctuations. Among the more important causes of drift may be mentioned:

(a) Slow changes in the battery e.m.f.
(b) Changes in the circuit resistances because of temperature changes.
(c) Slow changes in the characteristics of the tubes.

The most important sources of fluctuations are:

(a) Improper shielding.
(b) Poor rheostat contacts.
(c) Mechanical vibrations.
(d) Changes in the emission of the thoriated tungsten filament.

The first three causes of fluctuations and any effects due to temperature changes may be eliminated by proper design and mounting of the circuit and need not be further discussed. The elimination of drift due to slow changes in battery e.m.f. is an important problem. It can be solved by using a double-tube balanced circuit, as described by DuBridge.[1] However, on account of the high cost of the tubes, as well as the difficulty in obtaining two tubes of the same characteristics, it is desirable to use a single-tube circuit wherever possible. A single-tube circuit which can be "neutralized," i.e., made independent of battery changes, has been designed by W. Soller[2] and is shown in Fig. 1. In this circuit the galvanometer may be brought to zero by adjustment of R_o. If now the filament current of the tube is changed by changing R_5 the galvanometer deflection will change, but for some value of I_f will go through a rather flat minimum. By adjustment of R_4 the value of I_f at this minimum may be made approximately equal to the rated filament current of the tube, and the circuit is then neutralized. We have made considerable use of Soller's circuit in this laboratory and have made a detailed study of its characteristics. While it is definitely superior to previous single-tube circuits it has several disadvantages when high sensitivity is desired. It is the purpose of this paper to describe some modifications of Soller's circuit in which these disadvantages are eliminated.[3]

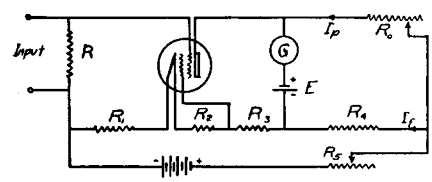

FIG. 1. Soller's balanced circuit.

[1] L. A. DuBridge, Phys. Rev. **37**, 392 (1931).

[2] Walter Soller, Rev. Sci. Inst. **3**, 416 (1932).

[3] While this paper was in preparation we were informed of the work of Turner and Siegelin which has since been published (Rev. Sci. Inst. **4**, 429 (1933)). They have also improved Soller's circuit but made no attempt to balance out fluctuations in filament emission as we have done.

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In the first place, while Soller's circuit may be made independent of changes in the storage battery, it is not independent of changes in the cell E. Slow changes in the temperature of this cell may cause not only a serious galvanometer drift, but a shift in the value of I_f at which neutralization may be obtained. Fig. 2 shows the changes in the neutralization curve caused by

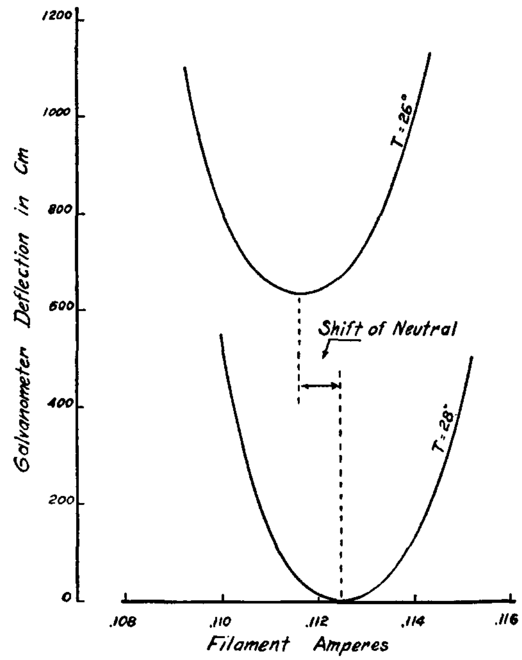

FIG. 2. Effect on neutralization curve of changing by 2°C the temperature of the balancing cell E.

purposely changing the temperature of the cell by 2°C. Even though the rate of drift may be made small by thermal insulation, nevertheless the changes from day to day necessitate frequent and rather tedious adjustments of R_4, in order to keep the value of I_f at the neutralization point approximately equal to the rated filament current of the tube. The value of R_4 required is rather critical and may change over wide limits with changes in E. We have developed a circuit in which the cell E is eliminated.

In the second place, no circuit hitherto designed has eliminated fluctuations due to changes in the filament emission of the tube, though a number of writers have recognized that for thoriated tungsten filaments this may be a serious cause of fluctuation.

THE NEW CIRCUIT

The circuit we have designed to preserve the advantages of Soller's circuit and to eliminate its shortcomings is shown in Fig. 3. As in Soller's circuit the proper control-grid bias and plate

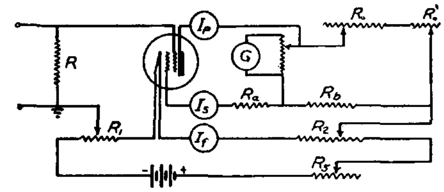

FIG. 3. New circuit for balancing out changes in filament emission.

potential are obtained by tapping off from the resistances R_1 and R_2 which are in series with the filament. The essential feature of this circuit, however, is the connection to the space-charge grid. Since this grid operates at a positive potential, it collects electrons, the current to it being, as a matter of fact, from four to five times as large as the plate current. Now if the filament emission changes for any reason, it would be expected that the currents to the plate and the space-charge grid would change in about the same ratio. Hence one may be balanced against the other, so that the galvanometer is unaffected. This turned out to be quite feasible.

Upon reference to Fig. 3, it is evident that the potential difference, e, across the galvanometer is given by $e=R_bI_s-R_oI_p$, provided the current through the galvanometer is small compared to I_p and I_s. (R_o' is small and is inserted merely for fine adjustment.) Actually we wish to make the galvanometer current zero, hence $e=0$ and

$$R_b/R_o=I_p/I_s. \quad (1)$$

This is the first condition to be satisfied. Obviously, once it is satisfied the galvanometer current will remain zero in spite of fluctuations in emission which change I_p and I_s in the same ratio. In addition we wish to have e independent of changes in battery voltage, and hence in I_f. That is, we set $de/dI_f=0$, which gives

$$dI_p/dI_f=(R_b/R_o)(dI_s/dI_f) \quad (2)$$

as the second condition to be satisfied for

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neutralization. It is easy to see that for conditions (1) and (2) to hold for a fixed value of R_b/R_o, it is necessary that the curves I_p *vs.* I_f and I_s *vs.* I_f be straight lines which intersect on the I_f axis. This will not be true in general, but it is found to be approximately true over small ranges of I_f so that quite satisfactory neutralization can be obtained. The condition is illustrated in Fig. 4 which represents an actual pair of curves for a typical FP-54 tube. It is evident

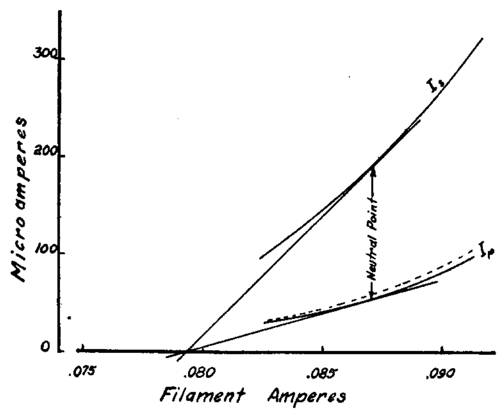

FIG. 4. Characteristic curves for FP–54 Pliotron in the circuit of Fig. 3, illustrating the condition for neutralization. The dotted curve shows the effect on I_p of changing the control-grid bias from 4 to 3.5 volts.

that in the vicinity of $I_f = 0.087$ amp. the curves are fairly flat and that tangents drawn at this point intersect on the I_f-axis. On inserting this tube in the circuit of Fig. 3 it was found in fact that the circuit was neutralized for $I_f = 0.087$ amp., which is sufficiently close to the rated filament current of 0.09 amp. The position of this neutralization point may be shifted by varying either the control grid bias or the plate potential, that is, by changing either the tap on R_1 or R_2.

In order to test the stability of this circuit it was arranged so that we could change from Soller's circuit to the new one by throwing a single switch, thus using the same tube and resistances. One circuit was balanced and neutralized and then a record made of the galvanometer reading over a period of three or four hours. The procedure was then repeated for the other circuit. The results are shown in Fig. 5. The galvanometer had a sensitivity of approximately 5×10^{-10} amp./mm. It will be noted that with the Soller circuit there was an irregular drift superposed on which were random fluctu-

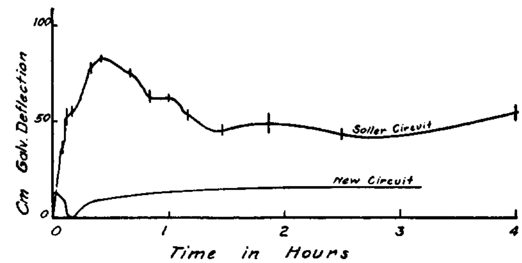

FIG. 5. Comparison of the stability of the new circuit with Soller's circuit.

ations whose range at various intervals is indicated by the short vertical lines. With the new circuit after the first 20 minutes the drift almost completely disappeared and there were no fluctuations of as much as 1 mm on the scale. In addition the new circuit had a voltage sensitivity about 20 percent greater than the other, because of the fact that a change in voltage of the control grid changes the plate current in one direction and the space-charge grid current in the other direction, giving a sort of push-pull effect on the galvanometer.

Such a circuit has been in use in this laboratory for several months in connection with some research on the photoelectric effect. It has given excellent service, and has required almost no readjustment. Furthermore, when it is necessary to replace the FP-54 tube for any reason the new tube may be balanced with only very slight and easily made changes in the resistances, in marked contrast to previous circuits we have used which had to be almost rebuilt whenever a new tube was installed.

Details of Construction and Manipulation

Fortunately it turned out that the values of the resistances in the circuit are not particularly critical, so that standard rheostats and resistance units may be used throughout if desired. To avoid troublesome sliding contacts we have used fixed wire-wound resistances wherever possible.

The values of R_1, R_2 and R_5 are chosen so as to give approximately the rated filament current of 90 milliamperes for the tube (110 milliamperes

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for the older tubes). With a 12-volt storage battery we used for R_1 and R_2 fixed resistances of about 50 ohms, made of manganin wire wound on a glass tube and fixed in place with sealing wax. Taps were brought out at approximately 10-ohm intervals to allow for adjustment. R_5 was a 50-ohm General Radio rheostat. R_o was a 10,000-ohm rheostat with a 50-ohm rheostat in series for fine adjustment. With R_o given, the value of R_b is determined by Eq. (1). Actually, however, the ratio R_o/R_b is between 4 and 5 for all the tubes we have tested and this ratio did not have to be changed when the tubes were changed, since it is not very critical. Consequently we used for R_b a 2000 ohm fixed resistance. The purpose of R_a is to give the proper bias to the space-charge grid, which is normally 4 volts. Hence the drop across R_a should be 2 volts if the plate potential is 6 volts. Since the space-charge grid current is of the order of 500 microamperes, R_a may be a fixed resistance of 4000 ohms. An ordinary Ayrton shunt is used with the galvanometer. R is a resistance of from 10^7 to 10^{11} ohms depending on the current sensitivity required.

While Eqs. (1) and (2) give the conditions for balance in terms of the characteristics of the tube, it is actually not necessary to determine these characteristics in order to balance the circuit. We have found the following manipulation most convenient.

(1) Connect up the circuit, adjusting I_f to approximately the rated value for the tube, and bring the galvanometer approximately to zero by adjustment of R_o. Have the galvanometer connected so that as R_o is decreased the deflection decreases.

(2) With the Ayrton shunt set at 0.1 or 0.01 slowly vary I_f by changing R_5, in such a direction that the galvanometer deflection is *decreased*. The galvanometer should then pass through a fairly flat minimum. If it tends to go off the scale before the minimum is reached, bring it back by changing to R_o again.

(3) If the value of I_f at the minimum differs from the rated value for the tube by more than 3 or 4 percent, shift the tap on R_2 to a new position and repeat. Two or three trials will usually locate the proper position for this tap. Typical neutralization curves for two values of R_2 are shown in Fig. 6.

(4) With the Ayrton shunt at 1.0 make a final adjustment for the minimum by adjusting R_5 and finally bring the galvanometer to zero with R_o. The circuit is now ready for operation. It may show a drift for 15 or 20 minutes until equilibrium has been established, after which time a slight adjustment of R_o will restore the balance.

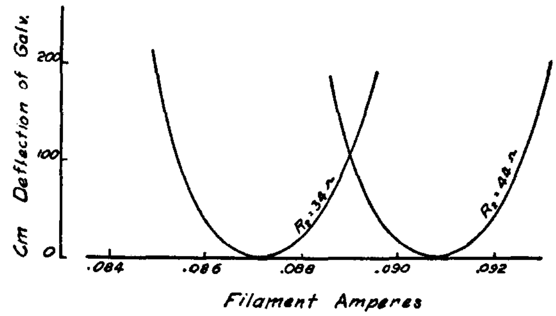

FIG. 6. Effect on the neutralization curve of changing the tap on R_2 by 10 ohms.

The tap on R_2 should be in such a position as to make the plate potential 6 volts positive with respect to the negative end of the filament, allowing for a drop of about 1 volt through R_o. If the position at which neutralization is obtained should give a value of the plate potential considerably below this the sensitivity of the circuit will be impaired, and it is better to move the tap back and find the neutralization point by changing the control grid bias slightly by moving the tap on R_1, or by changing the space charge grid bias by changing R_a. We have never found it necessary to change the grid or plate potentials by more than 0.5 volt from their rated values, or I_f by more than 3 milliamperes from the rated value, to locate the neutralization point. The FP-54 tubes purchased within the past year, with filament-current ratings of 90 milliamperes, are more easily balanced than the earlier tubes which have a current rating of 110 milliamperes. The newer tubes are more stable also.

With the galvanometer we are using we have found no difficulty in obtaining stable voltage

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sensitivities of 60,000 to 80,000 mm/volt and this might easily be doubled without great loss in stability by using a more sensitive galvanometer. If an input resistance of greater than 10^9 ohms is used fluctuations may be introduced, because of the great difficulty of shielding the grid circuit from high frequency disturbances. With a resistance of this value, our current sensitivity is of the order of 1.2×10^{-14} amp./mm which is great enough for many purposes. We have used resistances as high as 10^{11} ohms[4] with the grid leads and resistance in an evacuated container, but have not been able to eliminate fluctuations of a few mm. At any sensitivity, however, we have found the new circuit superior to any previous single-tube circuit we have used.

[4] Grid resistances greater than this value cannot be used without unduly increasing the time constant of the circuit. Cf. R. E. Burroughs and J. E. Ferguson, Rev. Sci. Inst. **4**, 406 (1933).

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