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Report on a
Vacuum Tube Current Amplifier
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Prepared by:	[redacted] Ramond C. Waddel, Associate Physicist.
Reviewed by:	Ross Gunn, Sup't. Mech. and Elec. Division.
Approved by:	A.H. Van Keuren, Rear Admiral, U.S.N., Director.
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ABSTRACT

A simple, stable, portable, current amplifier is described which is capable of amplifying d.c. currents of .5 microampere or larger to a value sufficient to actuate a recorder requiring 500 microamperes. Circuit, theory, and uses are described.

I. Introduction.

In the course of certain work it became desirable to continuously record small, fluctuating d.c. currents of uncertain polarity. The recording was to be done on an airplane, which forbids the use of an ordinary recording galvanometer. The device to be described amplifies the small currents to a value sufficient to actuate a rugged recorder or meter. No novelty is claimed for the circuit but it was felt that its simplicity and exceptional stability merit this publication in the hope that the device may find a wider application than that for which it was specifically designed.

II. Apparatus.

(A) Circuit -- A simplified circuit of the current amplifier is shown on Plate 1. The complete circuit is shown on Plate 2. From Plate 1 it is seen that the circuit is that of a conventional cathode follower, with the indicating meter, or recorder, in the cathode circuit, and provision for cancelling the static cathode current from the meter. The tube is self biased by R_B. The circuit is degenerative by an amount determined by the total d.c. resistance between cathode and ground, E_z shorted. From Plate 2 it is seen that provision is made for changing R_g, and therefore the current amplification, for bringing the meter resistances to some standard value (1500 ohms) by means of R_2 and R_{15}, and for slightly altering the feedback resistance for calibration purposes by means of R_{14} · R_{12} is the zero set control. Provision is made for quickly removing the input signal by means of a push-button (PB) when checking the zero, which is exceptionally stable. Since the device carries its own batteries and has an internal meter for measuring the amplified current, it may be regarded as a rugged, portable high sensitivity microammeter having full scale sensitivities of from 500 to .5 microamperes. By means of switch S_4 the indication may be transferred to an external meter or recorder.

(B) Theory -- The theory is simply that of a cathode follower. Referring to Plate 1 we see that

$$I_k = G_m E_g = G_m (E_s - E_k)$$

$$= G_m (E_s - I_k R_k) = G_m E_s - G_m I_k R_k$$

or

$$I_k + G_m I_k R_k = G_m E_s$$

or

$$I_k = \frac{G_m E_s}{1 + G_m R_k} = \frac{G_m R_g I}{1 + G_m R_k} \qquad (1)$$

now

$$R_k = R_b + \frac{R_z R_m}{R_z + R_m} \qquad (2)$$

$$I_m = I_k \frac{R_z}{R_m + R_z}$$

or

$$I_k = I_m \frac{R_m + R_z}{R_z} \qquad (3)$$

Substituting (2) and (3) in (1), and solving for the current amplification, we obtain

$$\frac{I_m}{I} = \frac{G_m R_g R_z}{(R_m + R_z)\left(1 + G_m\left[R_b + \frac{R_z R_m}{R_z + R_m}\right]\right)} \qquad (4)$$

Thus the amplification depends on **one** tube "constant," G_m, and the values of certain resistors. If it can be arranged that $G_m\left(R_b + \frac{R_g R_m}{R_z + R_m}\right) \gg 1$

then (4) approaches

$$\frac{I_m}{I} = \frac{R_g R_z}{(R_m + R_z)\left(R_b + \frac{R_z R_m}{R_z + R_m}\right)} \qquad (5)$$

which indicates complete independence of tube constants. Using circuit constants from Plate 2, with R_b = 1000 ohms, R_z = 5500 ohms, R_m = 1500 ohms, and G_m = 1700 micromhos (extrapolated from handbook data) the above condition for complete stability is satisfied to the extent that $3.7 \gg 1$. Thus the dependence of circuit performance on tube constants is here reduced, not to zero, but to about one fourth the value that would obtain if degeneration were not employed. Attempts to further approach ideal stabilization may include the use of a tube having a greater transconductance (with larger plate and grid currents), a larger value of R_b (which value is fixed by bias requirements), a larger value of R_z (discussed below), and a larger value of R_m (which soon entails the use of a more sensitive and less rugged indicating meter). The circuit constants shown in Plate 2 constitute about the best approach to the ideal stabilized condition that can be made with a single tube without encountering the difficulties parenthetically mentioned above.

Equations 4 and 5 show that the current amplification depends on the value of the zero adjusting resistor R_z. Since it is necessary to slightly alter this resistor from time to time this dependence is undesirable. It could be eliminated by making $R_z \gg R_m$, in which case equation (5) approaches

$$\frac{I_m}{I} = \frac{R_g}{R_b + R_m} \qquad (6)$$

where R_z does not appear. However to obtain a zero setting $R_z = \frac{E_z}{I_k}$,

so that increasing R_z requires an increase in E_z. With the total B battery complement fixed by considerations of space, weight, and current capacity E_z can only be increased at the expense of the plate supply E_{bb} with consequent reduction of G_m and permissible plate current swing.

The proportioning of the available supply (90 volts) between plate supply (67 volts) and bucking battery (22 volts) here used seems to be the best compromise. This immediately leads to a value of $R_z = 5500$ ohms, which is 3.7 times the value of R_m. This is sufficient to render negligible the effects of small changes in R_z on the current amplification.

If circuit constants from Plate 2 are inserted in equation 1, with $G_m = 1.7 \times 10^{-3}$ mhos, we obtain

$$\frac{I_m}{I} = 2.49 \times 10^{-4} R_g \qquad (7)$$

The value of the constant in the above equation was found, by direct experiment, to be 2.5×10^{-4}. This close agreement between theory and experiment is partly fortuitous, since circuit constants were not known to the indicated accuracy.

(C) Adjustment and Calibration -- Referring to Plate 2, it is seen that with the "Range" switch on position 2 the IN terminals lead directly to either the internal or external meter, except for R_{14} which should be here set at zero. It is necessary to bring both meter resistances to a value of 1500 ohms. Connect a good resistance bridge (L and N Test set, type S, 1.5 volt external battery) to the IN terminals and adjust R_2 and R_{15} so both meters have the above value, effectively.

A tube having a low grid current is necessary. Most new tubes will show a shift in the zero of the output meter when "Range" is thrown from position 3 to 11, thereby altering the grid resistor from 8000 ohms to 4 megohms. A tube having a minimum of zero shift should be selected and should then be "aged" in the amplifier (or externally) for several hours. With most tubes the zero shift becomes steadily less and, with a good one, will eventually become imperceptible.

If it is found that the zero setting is beyond the range of $R_{12}R_{13}$ should be slightly altered.

Next, a d.c. voltage of exactly 2.00 volts should be applied to the IN terminals, "Range" being on any position from 3 to 11, inclusive. The calibrating resistor R_{14} should then be adjusted so the meter current is exactly 500 microamperes.

If precision grid resistors have been used the calibration is now complete. If these resistors are found empirically they are of course so adjusted by trial that when measured nominal full scale input currents are applied full scale output is obtained, for each position of the Range switch. If each resistor is made of two selected half watt stock radio resistors values correct to one percent can be found with patience. These resistors of course have appreciable temperature coefficients.

Non-linearity due to inherent curvature of the transfer characteristic of a triode will be found to be less than one percent.

Input polarity is unimportant when center zero meters are used.

(D) Use as a Current Amplifier -- This device can be usefully employed as a current amplifier in situations where the internal impedance of the signal source is greater than a few thousand ohms. If the source impedance is small, a greater deflection will be obtained when the meter is directly connected to the source, rather than by using the vacuum tube amplifier. The use of the amplifier also assumes that the inclusion of the amplifiers' considerable input resistance in the source circuit is permissible. The above limitations are shared by all d.c. current amplifiers which use vacuum tubes without inversion.

Another point to be considered is the circuit modification when the push-button PB is pressed during a zero check. As shown in Plate 2, operating this push-button causes the apparent input resistance of the amplifier to suddenly change from some large value determined by the Range position, through infinity, to zero. The reaction of this change on the source circuit must be kept in mind.

When the Range switch is thrown from position 2 to 3 the output meter will be momentarily deflected off scale until the filament heats. This does no damage to a 500 microampere movement, but if a more sensitive movement is used it should be disconnected or shorted during this operation.

The stability of this amplifier is sufficient to warrant the use of an output meter with full scale sensitivity as great as 50 microamperes, although a refinement of the zero adjusting control will then be desirable. With such a meter the minimum input current for full scale will be .05 microampere, or an input voltage of .20 volt. The smallest detectable currents and voltages will then be about .001 microampere and .004 volts. The sensitivity can be still further increased by using larger grid resistors. At least another factor of ten can be so obtained, if a good tube is used.

The accuracy of the amplifier depends very largely on the values and stability of the grid resistors. Using radio resistors an accuracy of 4 percent of full scale on all ranges and including the effects of reasonable changes in temperature can be easily attained. With precision resistors the accuracy approaches that of the meters used.

A photograph of the current amplifier and the recorder (Esterline-Angus Graphic Ammeter Model AW, .5-0-.5 ma, 1350 ohms) it was designed to actuate is shown in Plate 3. The cabinet of the amplifier is 6 x 7 x 12 inches.

(E) Other Uses -- With the Range switch on position 11 the amplifier can be regarded as a d.c. voltmeter, requiring 2 volts for full scale (using a 500 microampere meter) and operating at 2 megohms per volt. The use of a suitable voltage divider extends this range upward indefinitely. In this application it compares well with such commercial instruments as Hickock Model 202 and the Volt-Ohmist and is definitely superior to these from a standpoint of zero stability. This latter superiority derives mostly from the fact that this instrment is battery operated. This frees it from line-voltage flucuations. It also leaves both input connections free to be above ground.

This device can be used as an ohmmeter. If the terminal voltage of a dry cell is first measured, using the device as a voltmeter, and then the cell be connected in series with an unknown resistor and the IN terminals the current flow can be measured. The total circuit resistance is calculated by Ohms' law, the amplifier input resistance subtracted, and the value of the unknown found. With a single cell resistors from about 2000 ohms to 10 megohms can be measured. Obvious circuit modifications and additions could be made to properly convert the device to an ohmmeter or voltmeter, without external auxiliaries.

The amplifier-recorder combination can be easily used with a photocell to continuously and accurately record light intensities. In this application the Range switch is set at position 11, and a B battery and photocell are connected in series with the IN terminals. With the further addition of a suitable light source and optical system the device can be used to amplify and record galvanometer deflections.

If one of the grid resistors is increased to about 10^9 ohms the device acquires some of the characteristics of an electrometer, being actuated by neighboring electrostatic charges. In this application the lower IN terminal and the case should be grounded. Difficulty will be experienced in keeping the zero on scale if a poor tube or too high a grid resistor is employed.

If a rectifier is properly connected to the input a.c. voltages can be read or recorded. The useful frequency range would of course be determined by the rectifier characteristics and could be made to extend through the audio range to high radio frequencies.

III. Summary.

A triode vacuum tube is used as a degenerative current amplifier. The linearity and zero stability are excellent. The output is sufficient to operate a rugged meter or recorder. The maximum current amplification is 1000, permitting a full scale reading with .5 microampere input. Uses as a d.c. or a.c. voltmeter, ohmmeter, photocell and galvanometer amplifier, and as an electrometer are also suggested.

AMPLIFIER CIRCUIT, SIMPLIFIED

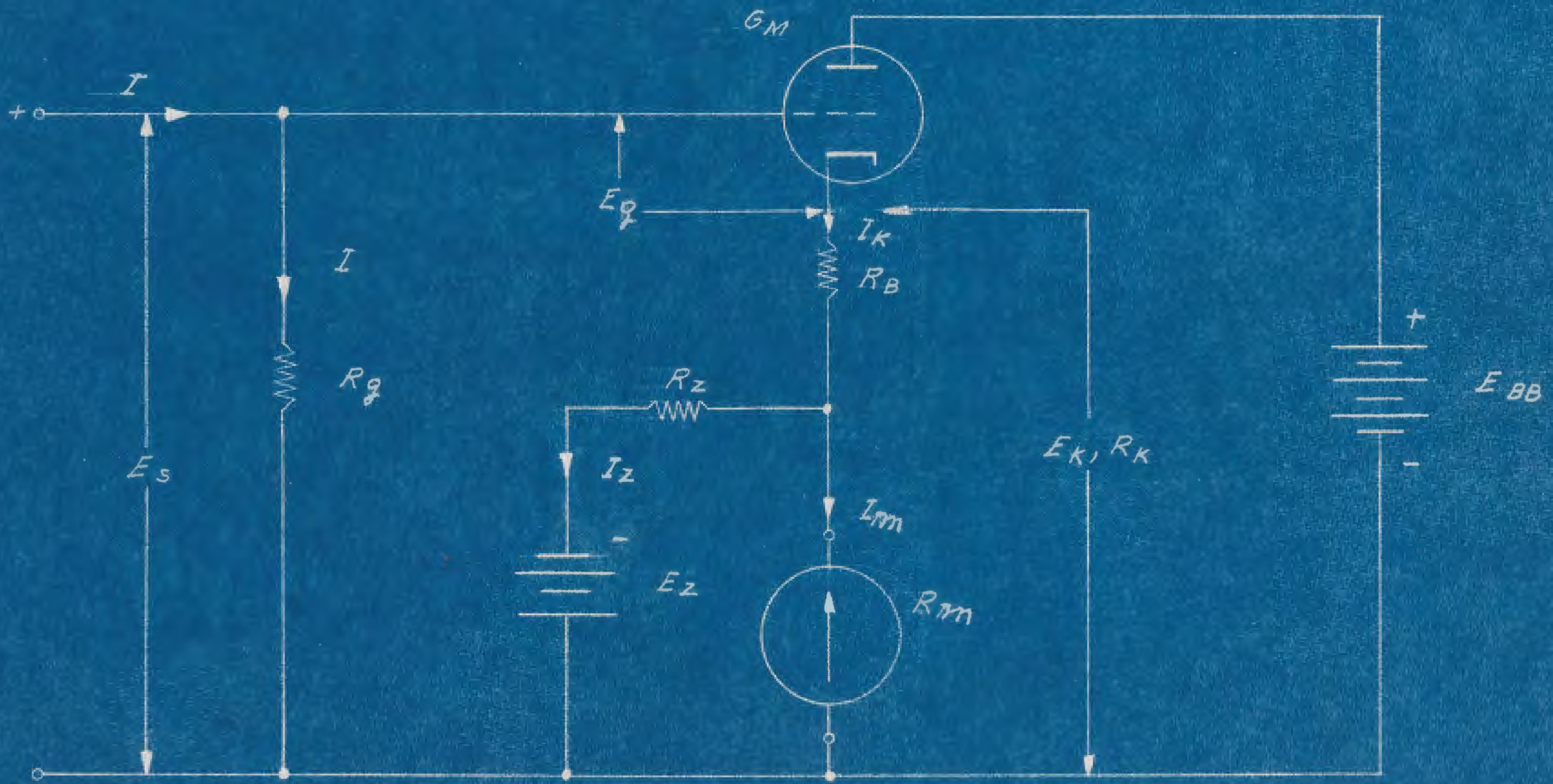
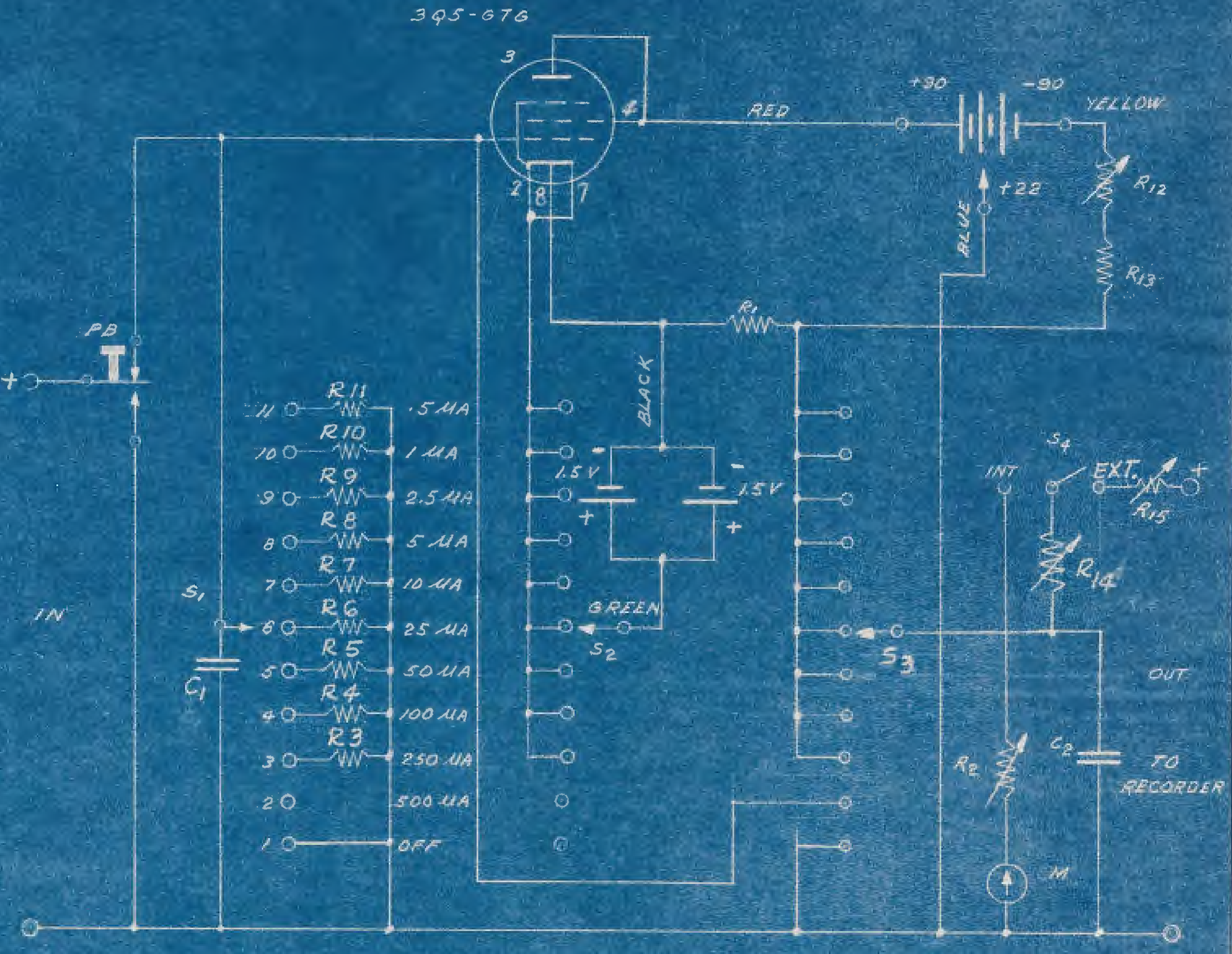


PLATE I

AMPLIFIER CIRCUIT



R_1 = 1K WW
R_2 = 2.5 K WW
R_3 = 8 K
R_4 = 20K
R_5 = 40K
R_6 = 80K

R_7 = 200 K
R_8 = 400 K
R_9 = 800K
R_{10} = 2 M
R_{11} = 4 M
(R_{12}) = 1K, WW

R_{13} = 5 K, WW
(R_{14}) = 500, WW (SCREWDRIVER)
R_{15} = 500, WW
C_1 = C_2 = .01 MICA.
(S_1) = (S_2) = (S_3) = 11 PT, SHORTING, GANGED AS "RANGE" SWITCH
(S_4) = SPDT TOGGLE

M = 500-0-500 MA   A BATT. = (2) 4 F.A. CELLS   B BATT. = (2) 5308 BATTS.

CABINET = 6 x 7 x 12 INCHES   A DRAIN = .1 AMP.   B DRAIN = 4 MA

(R) INDICATES PANEL CONTROL   PB = SPDT MICRO SWITCH

PLATE 2


METER
INT.
EXT.
RANGE
ZERO
OFF
FOR
E. A. RECORDER
1-OFF 5-50UA 9-2.5UA
2-500UA 6-25UA 10-1.0UA
3-250UA 7-10UA 11-0.5UA
4-100UA 8-5.0UA
COMPANY, INC.

PLATE 3