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DIRECT CURRENT AMPLIFIER

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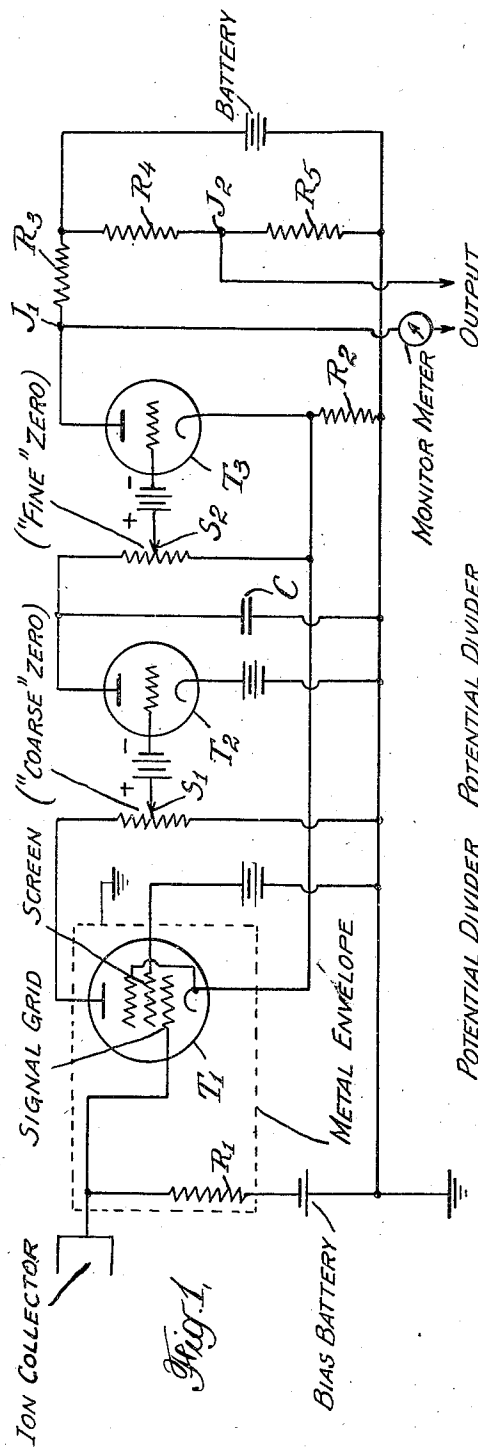


Fig. 1.

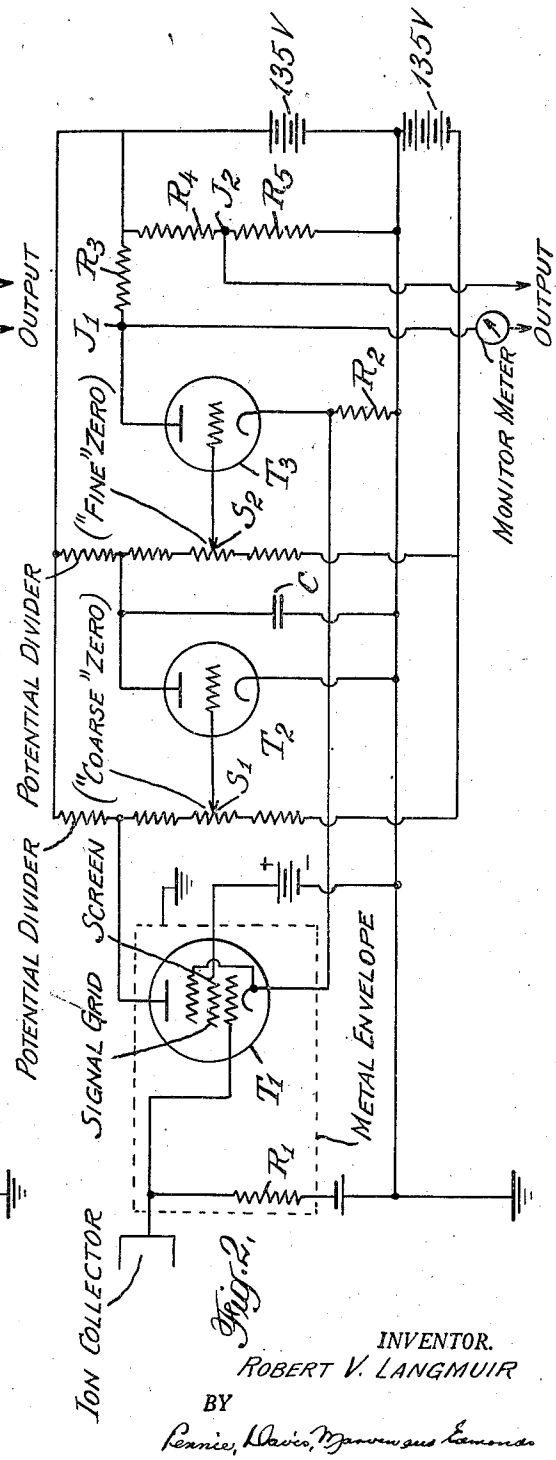


Fig. 2.

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DIRECT-CURRENT AMPLIFIER

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1 Claim. (Cl. 179—171)

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This invention is concerned with D. C. amplifiers for small currents and especially with D. C. amplifiers included in the output circuit of a mass spectrometer.

A mass spectrometer is an apparatus for sorting ions into a plurality of beams according to their mass-to-charge ratio, i. e., their specific mass. These different ion beams are directed at an ion collector, so that the currents they bear are discharged. The several ion currents thus produced represent the mass spectrum of the material being analyzed in the spectrometer, for example, a gaseous mixture of different molecular constituents—say a mixture of hydrocarbons.

The ion currents thus produced are very small and even when discharged through a large resistance of the order of 10^{12} ohms produce but a very low potential. They must be amplified greatly for purposes of recording and interpretation, for example by means of an amplifier connected between the collector and a recording galvanometer. In many types of mass spectrometers the beams are unidirectional and produce direct currents. The amplification of these small direct currents without distortion and while maintaining a high ratio of signal-to-noise is desirable.

There are several sources of noise in a D. C. amplifier, the term "noise" being employed to describe the randomly fluctuating signal that appears in an amplifier due to changes in elements thereof. Such noise is present even when no signal is being amplified and is generally of the same magnitude regardless of the strength of the signal. It may be due to the production of gaseous positive ions within the envelope of a vacuum tube due to the impression of potentials high enough to ionize residual gas therein, to thermal agitation of atoms and electrons within the input resistance, to statistical variations in the rate of electron emission from the cathodes of the vacuum tubes in the amplifier, or to the "flicker effect" which is apparently due to changes in the surface conditions of the emitting cathodes. These sources of noise are discussed at length by McDonald ("The thermionic amplification of direct currents," Physics, Aug. 1936) who states that heater tubes are too irregular in their action to be of practical value in D. C. amplifiers.

As a result of my investigations, I have discovered that, under certain conditions described in detail hereinafter, a heater type tube (specifically a type 38 tube, i. e. a pentode type of tube provided with a cathode [including heater filament] a control or signal grid, a screen grid, a suppressor grid and an anode or "plate" and having a gain, as connected, of unity) may be employed without difficulty and in fact with advantage as the first amplification tube in an inverse feedback operated D. C. amplifier, and that such an amplifier may be employed in place of an electrometer tube circuit having a large input resistance connected in the grid circuit, which has been proposed heretofore for amplification of small currents while maintaining a large signal-to-noise ratio, the term "electrometer tube" being employed to describe a tetrode type provided with filament, space charge grid, control or signal grid and anode or "plate," and having a gain, as connected, in substantial excess of unity, say in the neighborhood of 50. Such electrometer tube circuits usually incorporate the following features:

1. They utilize electrode potentials below the ionization potential of any residual gases within the electrometer tube.

2. The electrometer tube itself, the input resistance, and the lead to the ion collector are mounted in a highly evacuated chamber (pressure equals 1 to 10 millimicrons Hg).

3. Temperature compensating and battery voltage fluctuation compensating circuits are used to maintain uniform amplification factor.

The practice of the present invention does not require the use of electrometer tubes or of the voltage and temperature compensating circuits associated therewith. Instead, my invention contemplates (in a D. C. amplifier for small currents and including a circuit containing a plurality of amplifier tubes connected in tandem and a current indicator in the output of the circuit), the combination which comprises an input heater-type amplifier tube connected adjacent the input of the circuit and provided with a cathode, an anode, a signal grid and a highly evacuated envelope within which the anode, cathode and grid are disposed, means for imposing a negative bias on the signal grid, means establishing at the anode a positive potential, a negative feedback connected between the output and the input of the circuit, a grid resistor connected between the grid of the input tube and ground and adapted for connection to the source of small current, and a high resistance di-electric enclosing the grid resistor. A second highly evacuated envelope encloses the envelope of the input amplifier tube and in my preferred construction, at least one of these envelopes is conductively connected to ground.

Preferably, the input amplifier tube has an input signal voltage amplification factor that is greater than unity. Moreover, it is desirable to establish at the anode a positive potential below that at which gas present in the envelope may be ionized by electrons emitted from the cathode.

Another aspect of my invention contemplates a mass spectrometer provided with a D. C. amplifier including a circuit containing a plurality of tubes connected in tandem and a current indicator in the output of the circuit and also including the combination which comprises an input heater-type amplifier tube connected adjacent the input of the circuit and provided with an anode, a cathode, a signal grid and a highly evacuated envelope within which the anode, cathode and grid are disposed, means for imposing a negative bias on the grid, means for establishing at the anode a positive potential, a negative feedback connection between the output and input of the circuit, an ion collector in the mass spectrometer, a grid resistor connected between the grid and the cathode of the input tube and to the ion collector and the aforementioned second highly evacuated envelope.

In its preferred aspect, the amplifier of the present invention is a negative-feedback-operated D. C. amplifier utilizing a type 38 tube in its input or first stage, this tube being operated at the optimum heater filament current, (about 230 milliamperes) and with potentials beneath the ionization potential of any gases contained in the tube (i. e. potentials of less than 8 volts between any of the tube electrodes). The tube is operated with potentials which produce an amplification factor in this tube that is greater than unity and preferably of the order of 50. Moreover, as indicated above, it is desirable to place the tube in a highly evacuated chamber or envelope and to employ a large input resistance.

Because of the negative feedback of my D. C. amplifier, there is no need to provide temperature or voltage fluctuation compensation circuits. Moreover, noises which originate either in the plate circuit of the type 38 tube or in any of the subsequent circuits of the amplifier are negligible compared to the noise in the grid circuit. Hence the signal-to-noise ratio is maintained at a high level.

These and other features of my invention will be more thoroughly understood in the light of the following detailed description taken in conjunction with the accompanying two figures which are wiring diagrams of amplifiers incorporating the principles of my invention.

The circuits illustrated in Figs. 1 and 2 are the same except for differences in the manner of supplying potentials to the electrodes of the various amplifying tubes. In the apparatus of Fig. 1, the potential supply circuits are of a conventional type, but those of Fig. 2 utilize potential dividers between successive stages, these dividers being connected across a pair of batteries, the junction between which is grounded. Referring now to the figures, it will be observed that both circuits include three amplifier tubes T_1, T_2 and T_3 connected in cascade. The first amplifier tube T_1 is a type 38 tube, and is preferably operated with a filament out of about 230 milliamperes, a bias of -2 volts on its signal grid, and a plate voltage of less than about 8 or 9 volts with respect to cathodes. Its screen potential with respect to cathode should be about 5 volts.

Under these conditions the grid current is about 2×10^{-12} amps., and the effective internal resistance of the tube between the grid and cathode is about 10^{12} ohms. With a plate resistance of 0.5 megohm, the gain of the tube is about 100.

At the input of the amplifier, there is a large input resistance R_1 connected between the signal grid and ground. A small current such as that detected by an ion collector of a mass spectrometer passes through this resistance, thereby producing a voltage to be amplified.

With the tube operated as described hereinabove, the largest input resistance which it is possible to use is about 10^{10} ohms, but this resistance is small compared to the grid-to-cathode resistance, so that fluctuations in the latter produce no appreciable effect on the input voltage. There would be little advantage in making the resistance larger than about 5×10^{10} ohms in the present circuit, because the use of larger resistances will not improve the signal-to-noise ratio. This arises because thermal noise increases as the square root of R_1 while the shot noise and the signal increase in direct proportion to the input resistance. Because of this, an input resistance is used which has a value such that the noise due to the shot effect is somewhat larger than the thermal noise.

A resistance R_2 is connected between ground and the cathodes of the input and output tubes, T_1 and T_3. This resistance feeds back part of the output signal to the input circuit, thereby effecting stabilization of the amplifier according to well-known principles of negative feedback.

When the product $\mu\beta$ is very large compared to unity, where μ represents the total amplification of the tubes T_1, T_2 and T_3 without feedback and β represents the feedback ratio, the current amplification factor of the amplifier may be shown to be equal to:

$$\frac{R_1}{R_2}$$

The output circuit utilizes a resistance R_3 connected between the cathode and the positive terminal of a battery. The negative terminal of the battery is grounded, and two resistances R_4 and R_5 are connected in series to the positive and negative terminals respectively of the battery. The values of the resistances R_3, R_4 and R_5 are so proportioned with respect to the internal resistance of the ouput tube T_3 that the junction J_2 between resistors R_4 and R_5 is at about the same potential as the junction J_1 between the anode of tube T_3 and the resistance R_3. A current measuring or indicating device (not shown) may be connected between the junctions J_1, J_2. Such a current measuring device may comprise four galvanometer circuits of different sensitivity such as those shown as element 45 in Fig. 1 of the Hoskins-Langmuir patent application, Serial No. 437,922, filed April 6, 1942, now Patent 2,380,439, dated July 31, 1945.

In one of the leads to the output circuit, I utilize a monitor meter which is placed on the panel of the mass spectrometer so that visual indications are given of the intensities of ion beams striking the ion collector.

The signal grids of tubes T_2 and T_3 are connected to slide wire contacts S_1, S_2 of potentiometers included in the plate circuit of the preceding tubes T_1 and T_2, respectively. The movements of these sliding contacts change the biases on the tubes T_2 and T_3 and thereby control the amount of current appearing in the out-

put circuit and affecting the galvanometers, thereby affecting the "zero" output level, i. e., the galvanometer deflection corresponding to no input signal. The output current is more sensitive to changes in bias of the signal grid of tube T_2 than it is for tube T_3. For this reason, the sliding contact S_1 connected to the tube T_2 is called the "coarse" zero control, while that (S_2) connected to the grid of tube T_3 is called the "fine" zero control.

In order to shield the amplifier from electrostatic pickup, the evacuated envelope which includes the first tube T_1 and the input resistance R_1 is preferably made of metal.

In practice, the bias battery in the input grid circuit, the battery which supplies potentials to the screen, the filament supply for the input tube, and the feedback resistor and the plate resistance of the first tube are all mounted on a panel external to the evacuated chamber, and are connected to the appropriate part of the amplifier tubes through a shielded conduit.

In general, it can be shown that if the various stages of a D. C. amplifier are such that:

(1) $$e_n=\mu n e_{n-1}+k_n$$

(where e_n is the output voltage of the n^{th} stage and e_{n-1} its input voltage, and k_n is the output voltage of this stage when there is no input to the D. C. amplifier), the instability in the output voltage, de_0 due to some changes, dk_n, in the k's of the individual stages is:

(2) $$de_0=A\left(\frac{dk_1}{\mu_1}+\frac{dk_2}{\mu_1\mu_2}+\frac{dk_3}{\mu_1\mu_2\mu_3}\right)$$

The small changes dk_n may be due to changes in plate supply, screen voltage, etc. If the dk_n are all approximately the same and if the n's (amplification of factors) are all equal to 10 or more, the only important term is the first. To keep this term small it is important to have a large gain in the first stage of the amplifier. A in Equation 2 is the operating gain of the D. C. amplifier, which is approximately $1/\beta$.

From the foregoing, it will be seen that increasing the gain of the later stages to get more overall negative feedback will not reduce the zero instability due to unstable amplifier elements. This can only be done by increasing the gain of the first tube. But there is no advantage in increasing this too much, for other instabilities such as changes in the heater voltage, which the amplifier does not distinguish from an input, become of greater importance. Assuming a large $\mu\beta$, the only advantage in increasing μ is the improvement in linearity. The linearity of the present 3 tube amplifier, which has a $\mu\beta$ of about 35 db., is better than 0.1%.

I claim:

In a D. C. amplifier for small currents, including a circuit containing a plurality of amplifier tubes connected in tandem and a current indicator in the output of the circuit, the combination which comprises an input heater type amplifier tube connected adjacent the input of the circuit and provided with a cathode, an anode, a signal grid, a screen grid, a suppressor grid, and a highly evacuated envelope within which the anode, cathode, and grids are disposed, means imposing a negative bias on the signal grid, means establishing at the anode a positive potential, a negative feedback connection between the input and the output of the circuit, a grid resistor connected between the signal grid and ground and adapted for connection to the source of small current, a second highly evacuated envelope enclosing the envelope of the tube as well as the grid resistor and the connection between the grid resistor and the tube, at least one of the two envelopes being metallic and connected to ground.

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