THE USE OF A VACUUM TUBE AS A PLATE-FEED IMPEDANCE.

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In designing circuits associated with a screen-grid type of vacuum tube it is necessary always to satisfy the conditions imposed by the plate-circuit characteristics. These characteristics, although indicating an impedance of the order of thousands of ohms for the steady component of the plate-current, show the impedance effective for *changes* in current to be ten times as high or even higher. In circuits for use at high frequencies it is customary to feed the plate-current through a network the impedance of which is low for direct current but which is of the same order of magnitude as the higher value of tube impedance at the frequencies for which the circuit is designed. Thus by utilizing the frequency characteristic of the load circuit it is possible to obtain, for the steady plate-current, the low impedance required in order to avoid excessive drop in plate-battery potential, and at the same time, for the signal components, an impedance sufficiently high to avoid excessive loss within the tube. Although this utilization of the frequency characteristic of the load circuit is relatively easy at radio frequencies it becomes difficult in the audio range and is impossible in the case of a direct current amplifier.

At very low frequencies, then, it is necessary to find for the plate coupling of a screen-grid tube some impedance which will be reasonably low with respect to the total current flowing in the plate circuit but which shall be of the same magnitude as the tube impedance for any incremental changes in that current. Inasmuch as this is a characteristic of the tube itself what could be more logical than to use a similar tube for this coupling?

The use of a vacuum tube as the plate coupling impedance of an amplifier has been suggested a number of times. Mr. H. S. Reed,[1] of Bell Laboratories, has used a three element tube as the plate feed in a multi-stage direct current amplifier in such a way that the voltage drop across it would be substantially independent of normal variations in the potential of the plate-battery. Mr. John Mills,[2] also of Bell Laboratories, has proposed the use of a tube in voltage saturation, where the plate-current is independent of the plate-potential, as the equivalent of an infinite impedance. These applications were worked out prior to the advent of the screen-grid types of tube. The characteristics of these tubes, however, are such that they require, to a greater extent than do the triodes, an impedance of the type discussed. Moreover, these same characteristics make the tubes well suited to meet the requirements involved.[3] Quantitative measurements on a single stage of amplification using two screen-grid tubes of commercially available type, one as the amplifier and the other as the plate coupling impedance, have indicated performance characteristics which should prove of considerable practical value. In particular it has been found possible to build a single-stage direct current amplifier having a voltage gain of over 2,500 and a stability considerably greater than that of the equivalent multi-stage amplifier using the more conventional type of circuit.

THEORY.

To obtain an idea of the phenomena involved in a circuit arranged as suggested above let us draw a family of plate-current plate-voltage curves for a series of grid-voltages as parameter. The family shown in Fig. 1, is for an RCA-77 pentode having the screen-grid maintained at 22 volts. The performance which could be expected of this tube, using a pure resistance as the plate feed, is shown by drawing a straight line through the point of maximum plate-voltage and zero plate-current and through the operating point, or point

[1] Patent No. 1,403,566. Application filed July 11, 1919.

[2] Patent No. 1,548,952. Application filed Nov. 4, 1921.

[3] Since the completion of the experimental work here reported there has appeared, in *Electronics* for July, 1933, a note by Mr. E. R. Meissner describing an amplifier arranged in this way.

of zero signal input, *P*. The slope of this line is equal to the reciprocal of the resistance, the value in the example chosen being 1.6 megohms. As it indicates the voltage drop across the resistance for any given plate-current this line, by its intersections with the curves of the plate-current family, shows the distribution of the total plate-battery voltage between the tube and the resistance for the several values of grid-voltage. For a change in grid-voltage of 0.1 volt these curves show that the drop across the resistance changes by 21 volts.

To obtain a similar "load curve" for the case where a tube is used as the plate-feed impedance it is necessary simply to replot that curve of the family which corresponds to the fixed grid-voltage to be maintained on the coupling tube. The abscissa used will be the difference between the maximum plate voltage, or the voltage maintained across the two tubes in series, and the original variable plate-voltage. Although the tube presents the same impedance to the total plate-current at the operating point as does the resistance previously considered it is at once evident that the change in current for a given change in voltage corresponds to that obtained with a much higher resistance. Also the change in voltage across the tube for a given change in grid-voltage, is several times greater than that across the resistance, being 72 volts for a signal of 0.1 volt. In fact, to accomplish the same result with a resistance feed would require a resistance of 10 megohms (indicated by the reciprocal of the slope of the load curve) and a plate battery of 640 volts (indicated by its computed intercept on the plate-voltage axis).

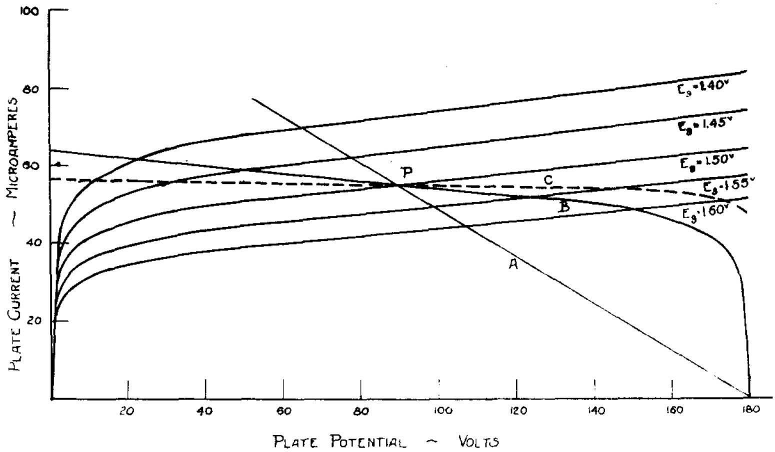
In spite of the simplicity of the circuit and the limited number of elements required there are several variables at our disposal. These are: first, tubes; and second, the potentials of the several electrodes. The selection of a suitable tube was restricted at the start to that group having 6.3 volt heaters as these are most convenient for operation from storage batteries, the use of which appeared wise from the standpoint of stability and of freedom from interference, especially during a preliminary investigation. Of the tubes in this group the 77-type was shown by a brief examination to have the greatest amplification under the conditions of the first adjustments. The data to be reported below were, therefore, taken with a pair of these tubes.

Turning our attention next to the terminal potentials on the coupling tube we see at once that the grid-bias may be obtained by introducing a suitable resistance between the plate of the amplifier tube and the cathode of the coupling tube and by bringing the grid of the latter to the negative end of this resistance. The circuit of Mr. H. S. Reed, to which reference has already been made, contains a similar resistance. Prof. C. E. Lansil of M.I.T. has pointed out that, unlike the grid-drop resistance of the conventional amplifier, such a resistance in the cathode lead of the coupling tube has a regenerative effect on the entire circuit. Inasmuch as the gain to be obtained in this way may be of considerable value this property will be examined in some detail.

The reversed tube characteristic drawn in Fig. 1, corresponds to a fixed value of grid-voltage; a similar characteristic, for values of grid-voltage depending on plate-current, may be obtained as follows. In Fig. 2 the data of Fig. 1 have been replotted to show plate-current as a function of grid-voltage, the parameter being plate-voltage. Points for the reversed tube characteristic already drawn are given by the intercepts on this family of a vertical line through the value of fixed grid-voltage. Through the desired operating point and through the zero point let us draw a straight line. This shows the value of grid-voltage resulting from the drop due to the plate-current in a resistance the value of which is given by the reciprocal of the slope of the line. Intercepts of this straight line and the curves of the plate-current family show the values of plate-current which must flow, when this voltage is used for the grid-bias, for each of the values of plate-potential, and hence furnish the data for the desire load curve. The points thus obtained are plotted on Fig. 1 as a dotted line. In this case the change in output voltage for an input of 0.1 volt is 110 volts.

It is evident that the limiting curve which can be drawn on Fig. 2 would be a horizontal line through the operating point. This would correspond to an infinite resistance and would require an infinite potential in series with the grid. By going to these limits the effect on the load curve would be

FIG. 1.



Load curves on plate characteristics of screen-grid vacuum tube.

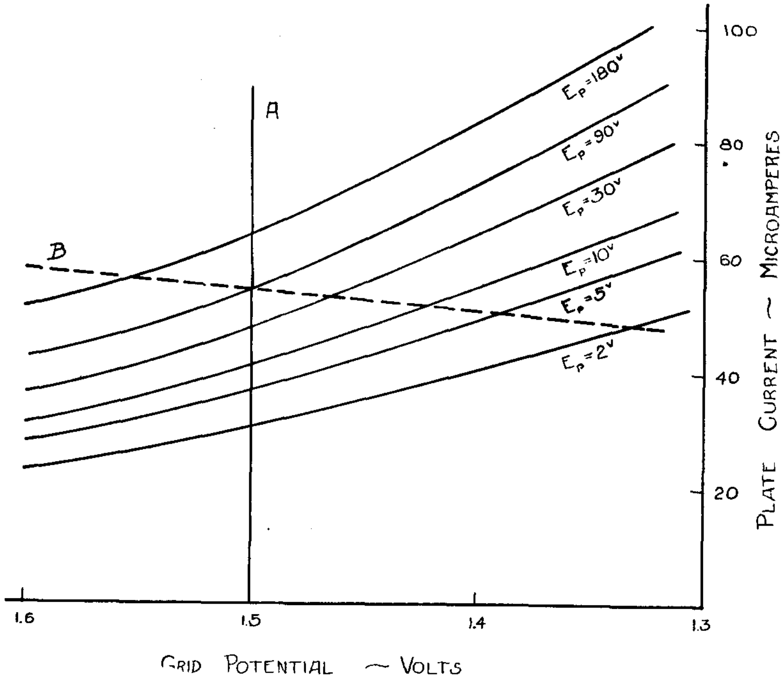
Tube: RCA-77 pentode.
Screen-potential: 22 volts.

(*A*) Load curve for resistance of 1.6 megohms as coupling impedance.
(*B*) Load curve for similar tube as coupling impedance, with fixed grid-bias of 1.5 volts and screen-potential of 22 volts.
(*C*) Load curve for similar tube as coupling impedance, with grid-bias from drop due to plate-current in resistance of 27,000 ohms in cathode lead and screen-potential of 22 volts.

to make it, in turn, a horizontal line through the operating point. This consideration of the limiting case indicates the impossibility of realizing a negative resistance by this method and assures us that the grid-bias resistance in the cathode lead may be used to increase the gain of the amplifier without danger of making the circuit unstable.

By definition the amplification constant of a vacuum tube is determined by two pairs of values of plate- and grid-potential, each giving the same plate current. A horizontal line through the plate-current curves therefore passes through such pairs of points. From this it follows that the voltage gain corresponding to this limiting case is equal to the amplification constant of the amplifier tube. When a fixed bias is used on the coupling tube the gain is equal to one-half this constant. In practice, then, it is possible to realize a gain greater than one-half the amplification constant, whereas with the pure resistance coupling originally considered the gain was considerably less than one-half the amplification constant.

FIG. 2.



Grid-bias curves on plate characteristics of screen-grid vacuum tube.

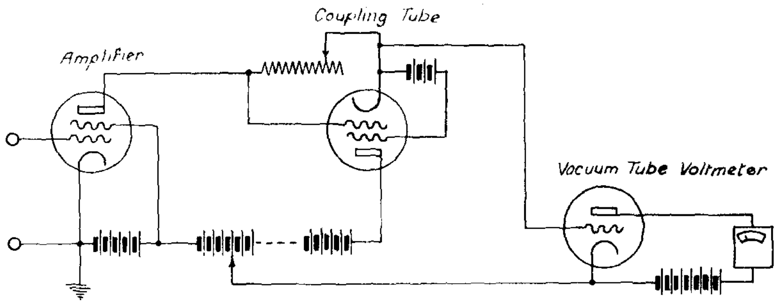
Tube: RCA-77 pentode.
Screen-potential: 22 volts.

(*A*) Fixed bias of 1.5 volts.
(*B*) Biased by drop due to plate-current in 27,000 ohm resistance in cathode lead.

PERFORMANCE.

Although the curves of Fig. 1 show the behavior of the tube-coupled amplifier in terms commonly used in vacuum tube circuit design problems and permit a computation of the relation between grid-voltage and plate-voltage, a more convenient and accurate determination of this characteristic may be made by direct measurement. For this a vacuum tube voltmeter was used. The arrangement of the circuit for this measurement is shown in Fig. 3. An RCA-89 tube was connected as a triode and calibrated for the voltage difference between grid and cathode as indicated by the plate-current through a low resistance milliammeter from a fixed plate-battery. The grid was connected to the cathode of the coupling tube and the cathode was connected to that point on the plate-battery which, for any given condition of the circuit, brought the grid-voltage of the voltmeter tube within the range of its calibration. The voltage across the coupling tube and plate-battery was then equal to the voltage of the portion of the plate-battery required less the voltage between the grid and cathode of the voltmeter tube as given by the calibration. It may be noted here that the grid of any output tube should not be connected to the negative end

FIG. 3.

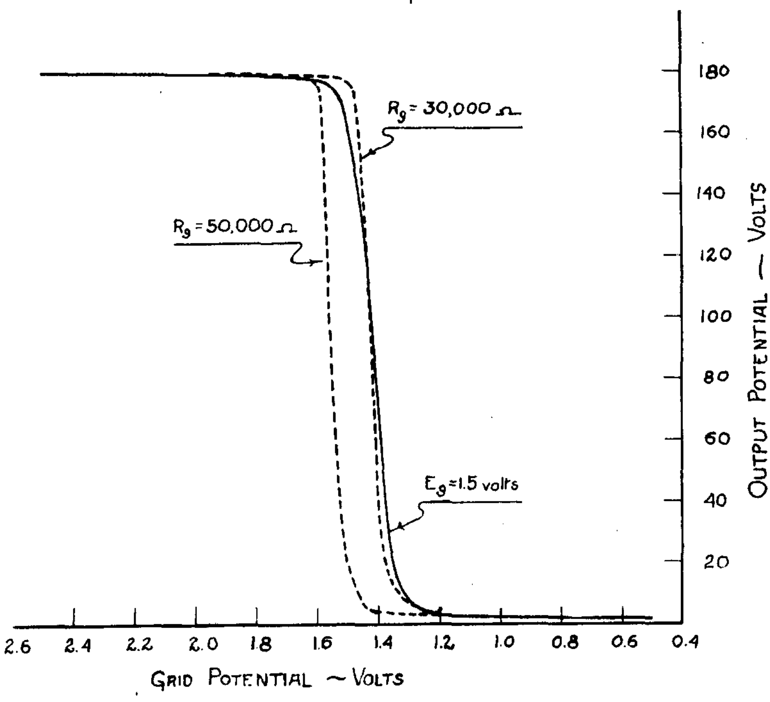


Tube-coupled amplifier with vacuum tube voltmeter for measuring amplification characteristics.

of the grid-voltage-drop resistance as any grid-current taken by the output tube, flowing as it does through both coupling tube and resistance, may cause the circuit to be unstable.

The curves of Fig. 4 show the relation between the voltage across both coupling tube and plate-battery, as measured by the method just described, and the voltage impressed on the grid of the amplifier tube. For these curves the screens of the amplifier and coupling tubes were each maintained at approximately 22 volts above their respective cathodes; the amplifier screen by means of a portion of the plate-battery and the coupling tube screen by a separate battery connected directly to its cathode. These curves give a good general idea of the operating characteristic of a tube-coupled amplifier using screen-grid pentodes. The scale required to show the entire curve, however, is such that an accurate estimate of the slope of the curve—or gain of the amplifier—cannot be made. In the laboratory study of this circuit, therefore, a direct measure of the gain was made by inserting in series with the variable grid-bias a resistance of one ohm through which a current of one milliampere could be passed, thereby making it possible to increase or decrease the potential of the grid of the amplifier by one millivolt. In this way it was found, when using a fixed grid-bias of 1.5 volts on the coupling tube, that the gain was approximately constant at 1,250 over the range of output potential between 50 and 170 volts. Using

FIG. 4.



Characteristics of tube-coupled amplifier.

Tubes: RCA-77 pentodes.
Screen-potential: 22 volts.
Total plate-potential: 180 volts.

a grid-bias obtained from the drop due to the plate-current through a resistance in the cathode lead the gain was found to be approximately 2,250 over the range of output potentials between 50 and 140 volts. These measurements also showed that the gain of the amplifier is not greatly affected by moderate changes in the magnitude of the grid-bias resistance. The curves of Fig. 4, however, show clearly the effect of this resistance in fixing the operating point of the circuit. In the design of a circuit for general use, therefore, it is possible to adjust the circuit to any desired value of potential across the output by adjusting this resistance.

It is interesting to note that the curve taken with a fixed grid-bias is more symmetrical than those for which the grid-bias is the drop in potential across a resistance carrying the plate-current. Although this current changes but little over the entire operating range of the circuit the effect is sufficient to alter the shape of the characteristic appreciably. For low values of negative grid-bias the current is limited almost entirely by the resistance of the coupling tube. As the bias is increased the resistance of the amplifier tube, and hence the potential drop across it, likewise increase. The decrease in plate-current, however, due to its effect on the grid-bias, causes the resistance of the coupling tube to increase at the same time, hence the knee of the curve is less abrupt at this end than when the resistance of the coupling tube is held constant by a fixed bias. For higher values of amplifier grid-bias, where the drop in potential is almost wholly across the amplifier tube, the effect of the bias resistance is to make the knee of the curve more abrupt than when a fixed bias is used.

The shape of the characteristic curve for this circuit at once suggests that it may have possibilities as a rectifier. Such is indeed the case. By adjusting the grid-bias to the value corresponding to the upper knee of the curve and applying a potential of 0.2 volt in series with the grid, at a frequency of 1,000 cycles per second, the potential on the grid on the vacuum tube voltmeter was reduced 50 volts. The circuit was also used as a detector for radio signals by connecting a tuned circuit in series with the grid of the amplifier tube and coupling to a short antenna. It was observed that, unless the grid-bias was accurately set to bring the zero-signal point onto the knee of the curve, no signals were heard in telephone receivers connected into the plate circuit of the vacuum tube voltmeter.

In the use of an amplifier such as this, stability is an important consideration. Tests were accordingly made to determine the effect upon the output potential—the potential across the coupling tube and plate-battery—of changes in the potential of the various batteries used. As was to be expected there are marked differences between a circuit using a fixed grid-bias and one using a bias resistor. For example: with a fixed grid-bias on the coupling tube the change in output potential is almost exactly one-half the magnitude of any change in potential of the plate battery. This is, of course, a natural consequence of the approximately equal division of the battery potential between two tubes essentially similar. When the bias resistor is used, however, the change in output potential is only about one-tenth the magnitude of any change in potential of the plate-battery. In this case the resistance is functioning as in the circuit described by Reed.[4] Again, with a fixed bias, changes in screen-potential on the amplifier or on the coupling tube produce equal effects on the output potential, a change of one volt on the screen-grid causing a change of about 55 volts in the output. An increase in screen-potential on the amplifier causes the output potential to fall whereas an increase in screen-potential on the coupling tube causes it to rise. When a bias resistor is used there is little change in the effect of the screen-potential of the amplifier tube; the change in output for a given change in screen-potential on the coupling tube, however, is reduced to approximately one-half that occurring with a fixed bias. These quantities, which are intended to indicate orders of magnitude, were obtained with a fixed bias of 1.5 volts or with a bias resistor of 50,000 ohms.

Although the primary purpose in building an amplifier in the manner described above is to obtain a circuit for amplifying steady, or slowly varying, potentials it is important to know the relation between frequency and gain. It is clear from the current and voltage values involved that the effective resistance between the point at which the output potential is available—the cathode of the coupling tube—and ground is of the order of several megohms and consequently that the capacity to ground of any circuit elements connected to that point will have a direct shunting effect on the output. Unfortunately it is necessary to connect the sources of both

[4] *Loc. cit.*

grid- and screen-bias to the cathode of the coupling tube. The capacitance of the cathode itself to the heater also constitutes a serious shunt across the output. On a circuit using screen-potentials of 22 volts and a bias resistor of 40,000 ohms measurements have shown that at a frequency of 250 cycles per second the output is reduced to about one-half the zero frequency value. The resistance of the plate circuit of the coupling tube may, of course, be reduced in a number of ways, although in general such reduction will be accompanied by a reduction in the gain of the circuit. For example, by increasing the screen-potentials on both amplifier and coupling tubes to 65 volts and reducing the bias resistance to about 1,200 ohms, thereby retaining the condition of approximately equal division of plate-potential between the two tubes, the gain at direct current is reduced from 2,500 to 175. Now, however, the circuit has constant gain to well above 2,500 cycles per second and has dropped only 1.3 decibles at 10 kilocycles per second. In fact, at some intermediate point, such as at a screen-potential of 45 volts and a bias resistance of 2,400 ohms, the circuit will have higher gain at high frequencies than with an adjustment which gives high gain at low frequencies. In other words, an adjustment which may be the best for direct current or for very low frequencies may well be the worst for frequencies in the upper audio range.

APPLICATION.

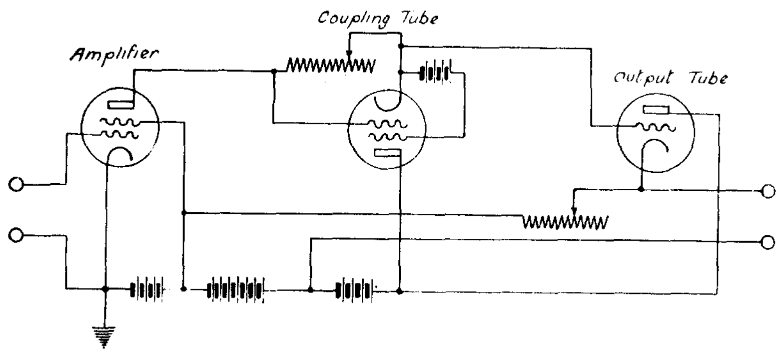
Although it is true that the high impedance of the circuit is a disadvantage when working with the higher audio frequencies it introduces very little if any complication with direct currents or at low audio frequencies. In order to work into circuits of low impedance it is only necessary to provide an output stage similar in arrangement to the vacuum tube voltmeter already described in connection with the gain measurements. The connections for this output coupling tube are shown in Fig. 5. Provided the impedance of the load is not great enough to cause injurious degeneration it may be connected into the cathode lead and current brought to the positive terminal through a suitable resistance from a point on the plate-battery of lower potential than that to which the cathode is connected. By adjusting this current to equal the normal space-current of the tube the current through the load may be reduced to zero for zero input-voltage, i.e., for the normal bias conditions on the voltage amplifier stage. In practice this neutralizing resistance may be adjusted to give zero current to the output when a fixed battery, having a potential equal to the normal operating bias of the output tube, is connected directly between its control-grid and cathode. By reconnecting the voltage amplifier and adjusting the grid-bias resistance of the coupling tube to again bring the output to zero it is evident that the voltage amplifier has been brought to the proper operating balance. It has been found that, allowing a sufficient time for the tubes to become thoroughly warmed up, the output current will remain at zero for long times without further adjustment. As previously pointed out readjustments of this grid-bias resistance may be made with but little effect on the gain of the amplifier. In general any necessary readjustments involve such small changes in the value of the resistance that it is well to provide a fine control in the form of a second rheostat having about one per cent. of the total resistance required.

An 89-type pentode, connected as a triode by bringing the No. 3 grid to the cathode and the No. 2 grid to the plate, has been found to be a suitable tube for connecting to low impedance loads. With the cathode connected to the 90-volt point on a plate-battery having a total potential of 180 volts and with a grid-bias of 6 volts the mutual conductance of this stage was approximately 1,800 micromhos. Preceded by a voltage amplification of 2,500 this results in an overall mutual conductance for the three tube circuit shown in Fig. 5 of 4.5 mhos.

The circuit arranged as outlined above has been found to work well into an oscillograph of the moving string, or moving coil, type. Because of the large currents which may flow while the circuit is being brought into proper adjustment it is well to provide a shunt for the oscillograph element. A meter may also be included in the output circuit to aid in making adjustments. It should, however, be removed, or short-circuited, before using the oscillograph in order to avoid the introduction of emf's due to the mechanical energy stored in the moving system.

The tube coupled amplifier, without the output circuit, has been found suitable for use directly on a cathode-ray oscillograph of the electro-static control type, the impedance of which is sufficiently high to cause a negligible increase in

FIG. 5.



Tube-coupled amplifier with output stage for low impedance load.

Amplifier tube: RCA-77 pentode.
Coupling tube: RCA-77 pentode.
Output tube: RCA-89 pentode connected as triode.
Grid-bias resistance: 30,000 ohms.
Plate-potential: 180 volts.
Screen-potentials: 22 volts.
Amplifier grid-bias: 1.5 volts.
Measured over-all mutual conductance: 4.5 mhos.

the shunt across the coupling tube. Using an oscillograph having a sensitivity of 0.2 mm. per volt, deflections of sufficient magnitude for most purposes were obtained on voltage waves having peak value of only 0.02 volt.

A circuit having the properties described is admirably suited to work involving photoelectric cells, the gain being adequate to control currents of sufficient magnitude to operate either meters or relays on very small changes in light intensity. The advantage of being able to use a direct-current amplifier for this purpose, thus eliminating any form of light chopper, is obvious.

The circuit has been tested in connection with the electromotive-forces associated with heart muscle action; the three tube circuit of Fig. 5 proved quite adequate for the operation of the counting relay used in the cardio-tachometer.

Tests have been made on a multi-stage tube-coupled amplifier. Although a two-stage circuit could be adjusted to give a gain of approximately 600,000, it exhibited the instability common to all multi-stage direct-current amplifiers. To realize the advantages of the tube-coupled amplifier in a multi-stage circuit it is evident that some form of compensation for potential changes will be required.

As in all vacuum-tube circuits the difficulties increase as an effort is made to increase the sensitivity. For moderate gains, of the order of 2,000 to one, however, the tube-coupled amplifier has been found to have advantages, both in simplicity of construction and in performance, over other types of direct current amplifiers previously used.