Measurement of the Chief Parameters of Triode Valves



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# XII. *Measurement of the Chief Parameters of Triode Valves.* *By* W. H. Eccles.

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1. When a tube is about to be put into use we require to know one or two commonplace facts concerning it, such as the appropriate filament current and voltage, which are easily found out or can be supplied by the maker. But there are other properties of the tube—such as the voltage ratio under conditions of normal use—which usually have to be specially measured, and which are essential for the formation of an accurate forecast of the performance of the tube in particular applications; for instance, in an amplifier or in a receiving set. A large number of parameters have been suggested for expressing numerically the various properties of triodes, but not all of them are equally important nor are all of them independent—that is to say, some of them can be deduced from others. By careful selection it may in time become possible to convey by quite a small number of parameters practically all the information requisite in practice. We shall, in fact, omit from the present section a number of suggested parameters or "constants," which depend jointly on properties of a tube and of the circuit it happens to be placed in, and we shall confine our attention to parameters belonging purely to the tube. Mixed functions of the tube and its circuits can usually be deduced from the data of the circuits of the true parameters of the tube itself.

2. At any given filament voltage or current the principal parameters of a triode are :—

(1) The co-ordinates of the mid-point of the straight part of the lumped characteristic.

(2) The voltage factor $g$.

(3) The differential co-efficient $di_a/de_a$ or $h_a$.

(4) The differential co-efficient $di_a/de_g$ or $h_g$.

Here $i_a$ represents the anode current, $e_a$ the anode voltage and $e_g$ the grid voltage relative to the filament; the quantity $e_a+ge_g$ is called the lumped voltage $e_l$ and the curve connecting the anode current with the lumped voltage is called the lumped characteristic.

If these parameters are all supposed to relate to the regular parts of the lumped characteristic and not to extreme and unusual adjustments, the last-named parameter is not independent of the preceding two since $h_g = gh_a$. Other data of importance (but not discussed in this Paper) are :—

(5) The value of the anode voltage which just fails to draw the full saturation current given by higher voltages.

(6) The differential co-efficient $di_g/de_a$ or $g_a$.

(7) The differential co-efficient $di_g/de_g$ or $g_g$.

(8) $di_a/de_f$ or $h_f$ and $di_g/de_f$ or $g_f$.

In addition, data concerning the knees of the characteristic curve are of value in connection with the use of the tube as a detector.

3. All these parameters belong wholly to the tube,—that is to say, they are not affected in value by the presence of the apparatus with which the tube is used and are, so far as is investigated, independent of the frequency. From a knowledge of these magnitudes the main aspects of the behaviour of the triode when connected to any kind of apparatus can be calculated. All of them can be deduced from the characteristic curves of a tube, but as the drawing of a number of complete curves is laborious we proceed to indicate various methods of determining the most important parameters direct.

4. The quantities $g$, $h_a$ and $h_g$ as well as some of the others are either mere ratios or are of the nature of conductances. Their measurement can, therefore, be reduced to the comparison of resistances, which can by the aid of resistance boxes be accomplished conveniently and accurately. But several of the measurements, notably those of parameters defined by differential co-efficients, are concerned with small changes in relatively large currents or voltages, and it is evident that if all of a large current is passed through a galvanometer the sensitiveness for small changes must be low. We therefore adapt some of the general methods of the physical laboratory to our purpose, methods such as the various resistance bridges, the compensation method, or methods using the differential galvanometer ; in all of which the galvanometer can be maintained in its most sensitive adjustment and be kept near its zero, although large currents are running in the things being measured. Only the compensation methods as developed by the writer are described in this Paper.

*Remarks on Direct-Current and Alternating-Current Methods.*

5. Direct-current methods have certain advantages over methods using rapidly alternating currents and a telephone receiver, though they are not so quick and convenient. An alternating current gives rise to alternating electric and magnetic forces round the various portions of the circuit it flows in, and these forces excite alternating E.M.F.s in neighbouring conductors and also in the different parts of its own circuit; in other words, the accidental electric coupling and magnetic coupling between portions of the same and other circuits produce E.M.F.s and these add subtly to the E.M.F.s applied for the purpose of the measurement. The effects are greater the higher the frequency of the alternations, and are usually too easily evident at ordinary acoustic frequencies. If these unwanted E.M.F.s happen to be in phase with the applied E.M.F.s it is possible to obtain silence in the telephone, but the balance adjustment so obtained will usually be farther wrong the stronger the induced stray effects. If, on the other hand, the stray E.M.F.s are not in phase with the applied E.M.F.s it is impossible to obtain a perfect balance.

In order to minimise these alternating-current disturbances it is well to run as much as possible of the connecting wiring through metal pipes, or to wind the insulated wires with lead or tin foil, and to connect all this metal covering to earth. It is necessary also to place coils in such relative positions that they have the least possible coupling with other coils, and to place condensers and other conductors of large surface well away from each other.

*Co-ordinates of the Mid-Point.*

6. The first important parameters are the co-ordinates of the mid-point of the straight part of the lumped characteristic. The most obvious and direct method for determining the lumped voltage of the corresponding current at the mid-point of the characteristic curve is to apply known grid voltage and anode voltage, to increase the latter until the saturation current is reached, to divide the magnitude of this by two, and then reduce either grid or anode voltage till the current becomes half of the saturation value. But the last step demands the use of calibrated sources of voltage, and as these are not always at hand, the following less direct method is recommended.

The connections are shown in Fig. 1. The galvanometer I ought to be of low resistance compared with that offered to the current by the internal path between anode and cathode. The filament E.M.F. or current must first be set at the desired stationary value by aid of the voltmeter V or otherwise, and the variable resistance $R$ made zero. Then increase the anode voltage $E$ by steps till the current as registered by the galvanometer I ceases to increase. Observe these values of

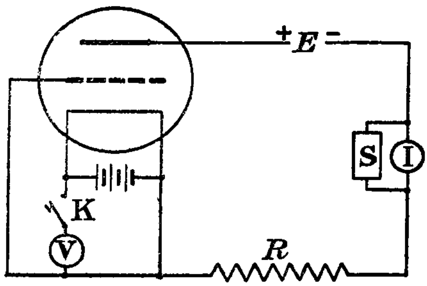


FIG. 1.

anode voltage and current and then add resistance $R$ to the anode circuit until the galvanometer reading is reduced to one-half the saturation value or $i_1$. Then the required coordinates are $i_1$ and $e_1 = E - Ri_1$. It should be noticed that this simple experiment gives information of great utility in connection with trials for amplifiers, for the voltage $e_1$ is that lumped voltage which must be applied to the tube in order to bring the steepest part of the characteristic into use; and if the voltage on the grid is zero, then $e_1$ is the voltage which must be applied to the anode. As an example, in a certain tube with a filament voltage of 5·2V a voltage of 300 secured a saturation current of 10 mA. By adding $R = 2800\,\Omega$ in series the current was reduced to 5 mA, the grid being connected all the time to the negative side of the filament. Therefore, $e_1 = 300 - 28 \times 5 = 160$V. The result is, it should be noticed, a lumped voltage; it may be made up by any anode voltage and grid voltage that satisfy the equation

$$e_a + ge_g = 160.$$

For example, if $g = 10$,

we may have $e_a = 100$ and $e_g = 6$

| | |
|---|---|
| 130 | 3 |
| 160 | 0 |
| 190 | −3 |
| 220 | −6 |

Any of these settings will give practically the steepest part of the characteristic.

*Compensation Method for Determination of $h_a$.*

7. The method to be described is applicable at any setting of anode and grid voltages. The connections are explained by Fig. 2.

The anode battery is indicated by $E$, the grid potential divider by PD. A sensitive galvanometer with its shunt at IS. The compensation circuit includes the galvanometer, the battery $e$ of smaller voltage than $E$, and the adjustable resistances $R$, $R_1$. The grid is permanently connected to the

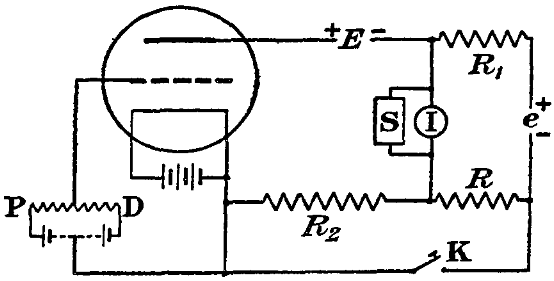


FIG. 2.

filament throughout the experiment and the grid voltage is, therefore, invariable. After the values of the anode, grid and filament voltages have been settled, the procedure is as follows: First, the galvanometer being shunted and the key K being closed, the resistance $R_2$ is given any value, $R$ a small value (between 10 and 100 ohms in the case of a receiving tube) and $R_1$ a larger value (about 1,000 ohms), and the latter adjusted until the deflection of the galvanometer is zero. Then the key K is opened and $R$ adjusted until the deflection is again zero. The shunt is now weakened, the key closed, and $R_1$ more accurately adjusted than before to obtain zero deflection, and then the key is opened and $R$ improved in adjustment. The process is repeated to any required degree of accuracy.

Zero deflection of the galvanometer implies that the P.D. between its terminals is zero. Therefore, when the key is open, the voltage applied in the anode circuit is $E-R_2i_a$; similarly, when the key is closed the voltage is $E$. Here $i_a$ represents the anode current when the key is open, and is equal to the current in the compensation circuit. Let $e$ represent the voltage of the battery in this circuit, then

$$i_a = \frac{e}{R_1 + R}.$$

The current when the key is closed is $e/R_1$. Hence, on closing the key the anode voltage increases by the amount $R_2 i_a$, and the anode current increases by

$$\frac{eR}{R_1(R_1+R)} \text{ or } \frac{R i_a}{R_1}.$$

Since the grid voltage is constant throughout the experiment, the ratio of the increase of anode current to the increase of anode voltage gives

$$h_a = \frac{R}{R_1 R_2}.$$

A telephone and interrupter may be substituted for the galvanometer in the above method, the procedure being precisely as just described. See §5 regarding experimental precautions.

The following measurements were made by students at the City and Guilds Technical College, using direct current. They found that when $R_2$ is taken of small magnitude $R$ must be finely subdivided in order to obtain accuracy. In the case below with $R_2 = 10$ ohms the subdivision of the resistance box used to supply $R$ was not fine enough.

| $R_2$. | $R_1$. | $R$. | $h_a$ |
|---|---|---|---|
| 10 | 930·7 | 0·7 | $7{\cdot}5 \times 10^{-5}$ |
| 200 | 928·6 | 13·0 | 7·00 |
| 800 | 927·5 | 52·0 | 6·88 |
| 1,000 | 926·0 | 65·5 | 7·1 |
| 1,045 | 924·0 | 67·0 | 6·9 |
| 1,200 | 927·2 | 78·0 | 7·03 |
| 2,000 | 927·9 | 130·1 | 7·06 |
| 5,000 | 928·9 | 323·5 | 6·95 |

Average value of $h_a = 7 \times 10^{-5}$
$E = 174$ volts.
$e = 8$ volts.

A measurement made by Mr. R. H. Rinaldi on another triode gave

$$R_2 = 2050, \qquad R_1 = 903, \qquad R = 43,$$

all in ohms, yielding $h_a = 2{\cdot}33 \times 10^{-5}$mho.

*Compensation Method for Determination of $h_g$.*

8. The method to be described is applicable to any setting of the grid and anode voltages, and is explained by Fig. 3. The grid is connected to the filament direct when the key K is depressed and through $R_3$ when the key is open. After the values of the grid, anode and filament voltages have been settled the measurement is performed as follows :—

The galvanometer being shunted and K open, the resistance $R$ is given a small value and $R_1$ a larger value, which is adjusted till the deflection of the galvanometer is zero. The

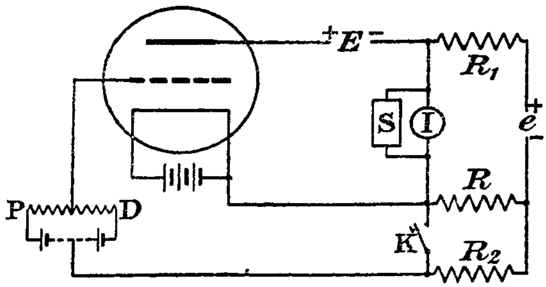


FIG. 3.

key K is now depressed and $R_3$ adjusted by trial till the deflection of the galvanometer is again zero. The shunt is then weakened, the key opened and $R_1$ adjusted more accurately than before. The key is depressed and $R_3$ again adjusted. The process is repeated to any required degree of accuracy.

When the key is down the current in the compensation circuit and therefore that entering the anode is determined by $R_1$ in series with $R$ and $R_3$ in parallel ; when the key is up this current is determined by $R$ and $R_1$ in series. In the former case the current being equal to $e$ divided by the resistance, is

$$\frac{e(R_3+R)}{R_1R_3+R_1R+R_3R},$$

and in the latter case is

$$\frac{e}{R_1+R}.$$

Hence, the increase of current when K is depressed, being the difference of the last two expressions, is

$$\frac{R^2e}{(R_1+R)(R_1R_3+R_1R+R_3R)}.$$

Again, when the key is down the voltage on the grid is that applied by PD ; when K is up the grid voltage becomes smaller by the amount of the potential drop along $R$, namely,

$$\frac{Re}{R_1+R}.$$

Moreover, the anode voltage is the same whether the key is up or down, since zero deflection of the galvanometer implies that the P.D. between its terminals is zero, and therefore that $E$ is the only voltage in the anode circuit. Hence, when the key goes from the open to the closed position the anode current and the grid voltage both rise, while the anode voltage remains constant, and therefore the ratio $di_a/de_g$ is

$$h_g=\frac{R}{R_1R_3+R_1R+R_3R}$$
$$=\frac{1}{R_1+R_3+(R_1R_3/R)}.$$

A telephone and interrupter may be substituted for the galvanometer in the above method, the procedure being precisely as just described. See §5 regarding experimental precautions.

A measurement made by Mr. R. H. Rinaldi, using the direct-current method, gave

$$R_3=90, \qquad R_1=907, \qquad R=43\text{ohms}$$

and $\quad h_g=3{\cdot}46\times10^{-4}$mho.

*Compensation Method for the Determination of g.*

9. In regular parts of the characteristics the voltage factor $g$ is equal to the ratio of $h_g$ to $h_a$, and therefore need not be determined separately if $h_a$ and $h_g$ have already been measured. In any case $g$ may be determined direct by the method sketched in Fig. 4.

The apparatus is the same as in the preceding paragraphs, except for the switch.

First, the compensation circuit is adjusted by variations of $R_1$, the switch being in the position marked 1 ; then the switch is moved over and $R_2$ is adjusted till the deflection is again zero.

When the switch is in the position 2 the anode voltage is $E-R_2i_a$, and the grid voltage is that applied by the potential divider PD. When the switch is moved to position 1 and zero deflection is obtained by varying $R_2$, the anode current is the same as before because made equal to the compensation current, which is unaltered. Moreover in position 1 the anode voltage is $E$ and the grid voltage is $Ri_a$ below that applied by PD. Thus the fall of the grid voltage $Ri_a$ neutralises the rise $R_2 i_a$ of the anode voltage and therefore

$$gRi_a = R_2 i_a$$

or

$$g = R_2/R.$$

When the grid current is extremely great, relatively speaking, an error arises in the above measurement because current is

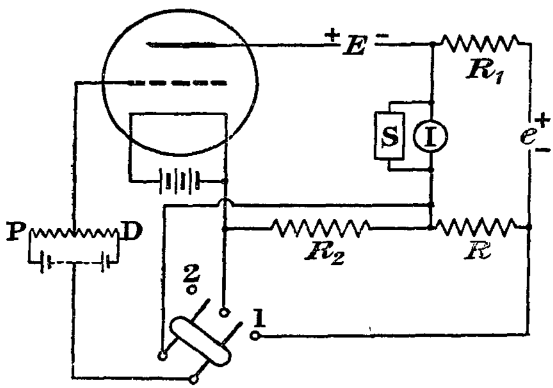


FIG. 4.

drawn from the compensation battery to the grid. This is, however, a rare event.

Measurements of $g$ by the direct-current method give pairs of values for $R$ and $R_2$, such as 50 and 900, 150 and 2,500, 220 and 3,960, all yielding 18 as the value of the voltage factor for the small receiving triode under measurement.

*Combined Apparatus for Determination of $h_a$, $h_g$ and $g$.*

10. The three methods of measurement just described may be carried out by the aid of the single piece of apparatus sketched in Fig. 5, wherein the letters have the same meaning as in Figs. 2 and 3. The special feature is the six-point switch with which is combined the key K of Figs. 2 and 3. Mercury pools are used in order to ensure good contacts.

Referring to the circuit diagram, when the switch is in the left-hand position marked *a* the connections are as required for determining $h_a$, as described in §7, balance of the galvanometer being sought for in both the up and down positions of the chopper key. When the switch is in the right-hand position marked *g*, the connections are those of Fig. 3, and $h_g$ may

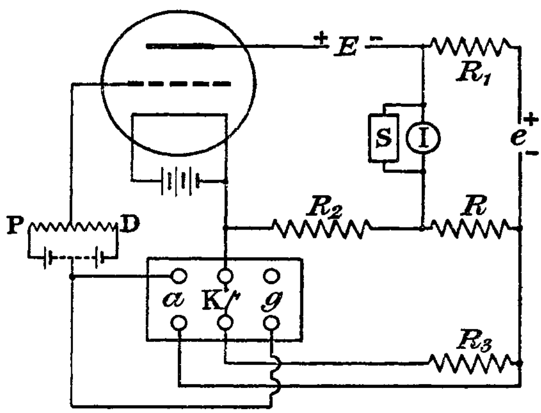


Fig. 5.

be determined by balancing the galvanometer for both the up and down positions of the chopper key. But when the magnitude of $R_2$ is so chosen that zero deflection is obtained when the switch is in either position with the chopper key up all the time, then the value of *g* is given by the ratio of $R_2$ to $R$, as explained in §9. In cases where the grid current is large, it is advisable to make $R_3$ zero during the determination of *g*.

## Appendix.

The following Papers deal with portions of the theory and describe methods of measurement bearing upon the points raised in the present Paper :—


T. Langmuir. "Pure Electron Discharge," "Proc." Inst. Radio Engineers, page 261, Vol. III.

M. Latour. "Discussion of the Audion," pp. 280-282, "The Electrician," Dec. 1, 1916.

G. Vallauri. "Comparative Experiments on Audions," "Elettrotecnica," pp. 335-342, June 23 ; and "Elettrotecnica," pp. 350-355, July 5, 1917.

J. M. MILLER. "A Dynamic Method for Determining the Characteristics of Three-Electrode Vacuum Tubes," "Proc." Inst. Radio Engineers, p. 141, June, 1918.

E. V. APPLETON. "A Thermionic Valve Slopemeter," "Wireless World," p. 458, Nov. 1918.

JOHN R. CARSON. "A Theoretical Study of the Three-Element Vacuum Tube," p. 187, "Proc." Inst. Radio Engineers, April, 1919.

STUART BALLANTINE. "The Operational Characteristics of Thermionic Amplifiers," p. 129, "Proc." Inst. Radio Engineers, April, 1919.

H. J. VAN DER BIJL. "Theory and Operating Characteristics of the Thermionic Amplifier," p. 97, "Proc." Inst. Radio Engineers, April, 1919.

H. W. NICHOLS. "The Audion as a Circuit Element," "Phys. Rev." 13, pp. 404-414, June, 1919.

W. H. ECCLES. "An Investigation of the Internal Action of a Triode Valve," "Radio Rev." Oct., Nov., Dec., 1919.

——. "Vector Diagrams of some Oscillatory Circuits used with Thermionic Tubes," "Proc." Phys. Soc. April 15, 1919.

## ABSTRACT.

At any given filament voltage or current the principal parameters of a triode are :—

1. The co-ordinates of the mid-point of the straight part of the lumped characteristic.
2. The voltage factor $g$.
3. The differential coefficient $di_a/de_a$ or $h_a$.
4. The differential coefficient $di_a/de_g$ or $h_g$.

Methods of determining these quantities are described.

## DISCUSSION.

Prof. FORTESCUE said the author had described some very nice methods for getting certain parameters of a valve; but he felt they were somewhat academic. There were two aspects in all these problems, namely, the practical and the instructional, and he thought Dr. Eccles had allowed the latter to predominate in devising the methods. For practical purposes one would frequently want to test the complete characteristic of a valve, and he would, on the whole, prefer the old arrangements. He did not think the author had emphasised sufficiently the importance of maintaining the filament current at a pre-determined value. The methods which he mentioned would give great accuracy, but they would be sensitive to very small variations of the filament current.

Prof. G. W. O. HOWE said that the suggestion of a single "lumped" characteristic was attractive, yet in practical work it was very desirable to have the various characteristics for different grid voltages. He had been rather mystified by the author's opening remarks concerning Ohm's law.

To say that a valve obeyed Ohm's law when all the "constants" concerned follow complicted laws for different voltages and currents appeared to be stretching the meaning of Ohm's law to an inadmissible extent.

Prof. O. W. RICHARDSON emphasised the remarks of the previous speaker regarding Ohm's law. He could see no reason for saying that Ohm's law applied where the resistance varied with the current and voltage.

Mr. F. E. SMITH thought the methods given by Dr. Eccles would be exceedingly valuable where large numbers of valves had to be tested. He would like to emphasise Prof. Fortescue's caution about the constancy of the filament currents.

Prof. A. O. RANKINE said: There is a point in connection with triodes concerning which I wish to ask the advice of the author. It refers to the use of triodes in that extreme case of low frequency, namely, when the voltage to be amplified is constant. Suppose that this E.M.F. is associated with a circuit which can be made of very low resistance, such, for example, a thermo-electric E.M.F. In that case, in the absence of means of amplification, the most sensitive arrangement is that in which the resistance of the measuring galvanometer is as low as may be consistent with galvanometric efficiency. The question is whether, in these circumstances, amplification of voltage by one or more triodes will be actually advantageous. If the limitation which I suspect does exist, it is important that the fact should be known; if it does not, the knowledge is, perhaps, of even greater importance, in view of the wide additional field which would be opened for the application of triodes. But, in either case, an authoritative opinion is required. The view I take of the question, subject to correction, is as follows: The output voltage of a triode is necessarily in a circuit of high resistance, for the latter includes the space between filament and plate, and it is therefore measured most efficiently by a detector of high resistance or impedance. But when the input voltage *need* only be in a circuit of *low* resistance, the fact that the E.M.F. is amplified by the triode may not be sufficient to compensate for the original loss of power involved by connecting the input voltage to the filament and grid, between which the resistance is large. A numerical example may be used to illustrate this point. Suppose that the E.M.F. to be amplified is $E$, and that it is associated with a resistance of 5 ohms. The most efficient galvanometer for direct measurement would have 5 ohms resistance. Thus, the current would be $E/10$ and the *power* operating on the galvanometer $\frac{E}{10} \cdot \frac{E}{2} = \frac{E^2}{20}$. Now, suppose the triode gives a voltage amplification of 10, and that the resistance between filament and plate is 50,000 ohms. In this case 50,000 ohms is the best resistance for the galvanometer, the current is $10E \times 10^{-5}$, and the power available $10^{-4} \cdot E \times 5E = \frac{E^2}{2,000}$, or only 1 per cent. of that obtained without the triode. Thus, several more triodes in cascade would probably be required to make up the leeway lost in the first, involving considerable increase of apparatus and multiplication of valve disturbances. The objection does not, of course, apply to the amplification of alternating and intermittent voltages, even when they occur in low resistance circuits, for in such cases the E.M.F. can be transformed up, without considerable less of energy, before being introduced into the triode.

Dr. ECCLES, in reply, said that as regards the objections raised to mentioning Ohm's law in connection with the complicated actions in a triode vacuum tube, he thought it admissible to consider that Ohm's law applied instantaneously at any point of the curve connecting the space charge current with the E.M.F. applied between anode and cathode because the value of the current is obtained by dividing the sum of the E.M.F.s (including the back E.M.F. due to space charge) by the resistances (including the differential resistance). Both back E.M.F. and differential resistance are constant during an infinitesimal change of current and E.M.F., because they belong to the tangent line of the characteristic curve. In reply to Prof. Rankine, leaving aside rapidly varying currents and voltage, the use of a single triode valve for amplifying slowly varying currents or voltages is, as a rule, advantageous only when the supply of energy is strictly limited, and is in the form of a small quantity of electricity at relatively high potential or as a small current in a very high resistance. In such cases if the energy can be conveyed to the grid of the triode and spent in raising its potential. The release of energy in the anode circuit is very much greater and is in convenient form. In the case of the low-resistance thermo-junction problem suggested by Prof. Rankine the junction is a heat engine supposed provided with a source of heat capable of supplying energy for any length of time, and at a rate very largely in excess of what can be consumed in exciting the grid of the tube; therefore, the use of the triode can add neither to the convenience nor to the sensitiveness of the direct galvanometer method. Of course, if on any occasion a very high resistance galvanometer were the only one available it would be better to use a triode, or a sufficient number of triodes in parallel, with anode resistance approximately equal to that of the galvanometer.