MEASUREMENT OF POTENTIAL DIFFERENCE

POTENTIOMETER*

A potentiometer is essentially a piece of apparatus by means of which e. m. f.'s are compared. If one of the two e. m. f's is known, the other may be determined by comparison with the known one, and thus the potentiometer is used for the measurement of e. m. f.'s by comparison with a standard e. m. f. It may also be applied to the measurement of current and resistance by methods which are described and discussed below.

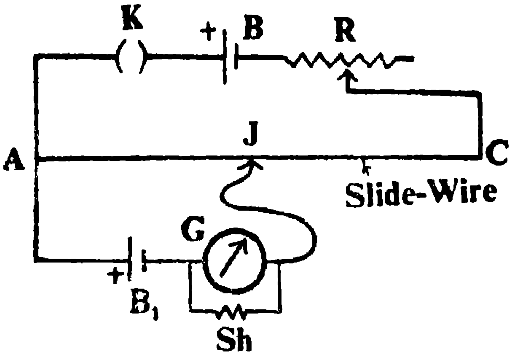

Fig. 60
Principle of a potentiometer

The principle of the potentiometer is illustrated in fig.-60, which shows the connections of the most elementary form. A battery B sends a current through a slide-wire AC of uniform cross-section, R being a variable resistance to limit the slide-wire current. B_1 is a cell whose e. m. f is to be measured. This is connected in series with a galvanometer and a jockey J which slides along the wire. The polarity of B_1 is as shown in the figure.

Suppose that ρ is the resistance *per unit length* of the wire, and that i is the current when the jockey is not pressed. Then if the length AJ is l, the voltage drop across AJ is i ρ l.

If the jockey J is now pressed, a current will flow through the galvanometer in the direction AGJ if the voltage drop across the length l of the slide-wire is greater than the e. m. f. of the cell B_1. If the e. m. f. of the cell is greater than the potential difference between A and J, the current in the galvanometer will flow in the

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* For further study of this apparatus read author's book "A Critical Study of Practical Physics and Viva-Voce."

reverse direction. If these two are equal no current will flow through the galvanometer.*

Suppose now that the e. m. f. of two cells B_1 and B_2 are to be compared. Then, the first cell B_1 is inserted, as shown in fig.-60, in series with the galvanometer, and the jockey J is adjusted on the slide-wire until no current flows through the galvanometer. Let that balancing length be l_1. B_1 is then replaced by B_2 and the jockey again adjusted until no current flows through the galvanometer. Let this new length be l_2.

Then, if E_1 = e. m. f. of cell B_1

E_2 = e. m. f. of cell B_2

we have† $E_1 = i \rho l_1$ and $E_2 = i \rho l_2$

so that

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

A scale is provided in this ordinary form of the potentiometer, so that l_1 and l_2 may be read off, and the ratio l_1/l_2 gives the ratio of the two e. m. f.'s as shown above.

If one of the cells (say B_1) is a standard cell‡ of known e. m. f., the e. m. f. of the cell B_2 given by

$$E_2 = \frac{l_2}{l_1} . E_1$$

In the above experiment it is essential that the supply battery B is of ample capacity so that the current i in the slide-wire may remain constant throughout the test. A resistance should be connected in series with the galvanometer—or a shunt used—for protection during the initial stages of adjustments of the jockey J, this shunt being cut out as the position of zero deflection is reached. Such a resistance is also necessary in order that no appreciable current shall be taken from the standard cell, when inserted in the galvanometer branch, during the preliminary adjustment of the jockey. *The e. m. f. of the standard cell cannot be relied upon if it is allowed to give any appreciable current.*

It should be noted that when the potentiometer is balanced no current is passing through the cell under test, so that the e. m. f. measured is the open circuit e. m. f. of the cell.

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* The cell B_1 is connected in such a way that it *opposes* the passage of the current due to the potential difference between A and J.

† Obviously, both E_1 and E_2 must be less than the e. m. f. of the supply battery B.

‡ For instance, it may be a Weston cadmium cell whose e. m. f. at 20°C is equal to 1·0184 volts.

Obviously, in the above ordinary form of the potentiometer the accuracy of measurement depends to a large extent upon the accuracy with which ratio l_1/l_2 can be determined. For making such a comparison, the accuracy of the determination depends on the accuracy of obtaining the balance point. If instead of using a 1 metre potentiometer (as in the above case), a wire of 10 metre length be used, then each cm. of wire has a potential drop equal to one-tenth the drop in the simpler potentiometer, *i. e.*, a movement of 1 mm. in the single wire would correspond to 1 cm. movement in the 10 metre instrument. Hence, by using a 10 metre potentiometer the true balance point can be very easily and more accurately located.

But the use of many wires involves two serious difficulties, (i) the apparatus becomes cumbersome, and (ii) it is difficult to get a very long wire of absolutely uniform cross-section throughout its entire length—a condition which is essential for the precise performance of the instrument as demanded by theoretical considerations given above. In the modern forms of the potentiometer designed for precise measurements, these difficulties have been overcome and the effect of a very long wire is obtained by connecting a number of resistance coils in series with a comparatively short slide wire, as given below.

This pattern (fig.–61) of the potentiometer consists of ten coils arranged in line with one stretched wire of platinoid, 50 cms. in length and of uniform cross-section, and its resistance is adjusted to 1 ohm. The resistance of each coil is equal to that of the wire. On the scale provided along the slide wire each cm. is indicated as two.

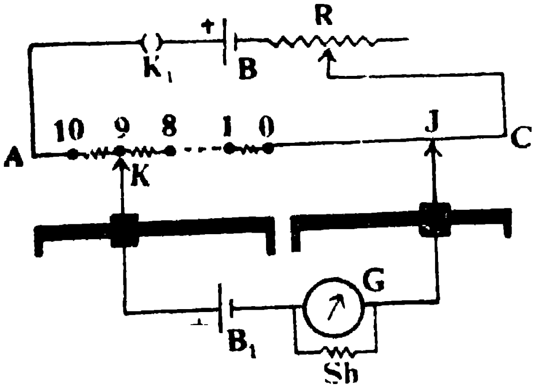

Fig. 61
Connections with 11-wire potentiometer

The special feature of the instrument is that not only the contact maker J, connected with the negative terminal of B_1, but its positive terminal connected to another contact maker K, moving over the studs of the coils, is also movable. By taking 10 coils and 18·4 cms. on the wire, against a Weston cadmium standard cell the potentiometer wire is accurately calibrated* and then it indicates 1 millivolt per cm.

* If only a Daniell cell is available in the laboratory as a standard cell (e. m. f. = 1·1 volt), its e. m. f, can be balanced on all the eleven resistances including the wire. Thus, the fall of potential across one coil will be very nearly equal to 1·1/11 = 0·1 volt, and the wire indicates as before 1 millivolt per cm.

Crompton's Potentiometer

It is a compact and precision type of potentiometer in which the sensitivity of the instrument is considerably increased, and at the same time its accuracy is not sacrificed. A simplified figure, depicting the essential features, is depicted in fig -62.

A graduated slide wire is connected in series with fourteen (or more) coils, each of which has a resistance exactly equal to that of the slide wire (of the order of 10 ohms). There are two contact makers J and K, sliding along the slide wire, and the studs of the coils respectively, R_1 and R_2 are two variable resistances, the former consisting of a number of coils used for coarse adjustment of the potentiometer current and the latter taking the form of a slide wire for fine adjustment.

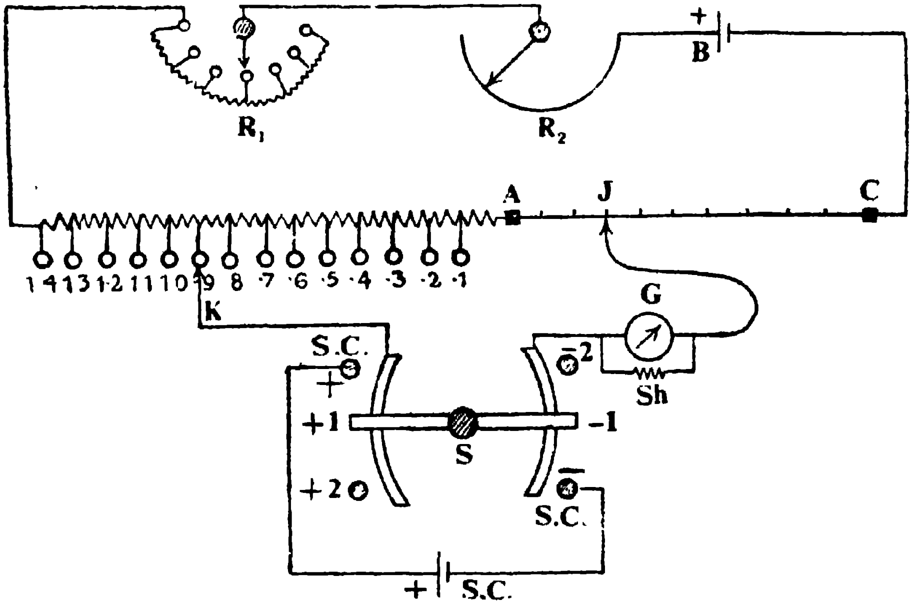

Fig. 62
Crompton's potentiometer

The galvanometer G is connected to a multiple circuit switch S, with the help of which either the standard cell (S. C.), or other E. M. F.'s to be measured, can be connected in the galvanometer circuit. The terminals to which the source of unknown E. M. F. is connected are marked positive (+) and negative (—) to avoid the possiblity of damage to the potentiometer due to the wrong polarity being used. The standard cell as well as supply battery terminals are also marked similarly.

[Note—It is very important that there shall be no appreciable thermo-electric E M.F.'s within the potentiometer itself, since such extraneous E. M. F.'s shall affect the readings. For this reason, manganin, which has a very low thermo-electric E. M. F. with copper, is usually chosen as the material for the slide-wire as well as the resistance coils. To ensure further that all parts are at a uniform temperature, all contacts and joints in the potentiometer circuit are included in the case of the instrument. This procedure also ensures the protection of the joints and contacts from the atmosphere. This is essential since any acidity of the atmosphere causes corrosion of the contacts and may set up small voltaic E. M. F.'s at the joints. To avoid corrosion the contacts are often made of a special gold-silver alloy.

Further, in order to avoid leakage between adjacent parts of the potentiometer circuit, it is essential that insulation is perfect. It is for this reason that the working parts of the instrument are mounted on an ebonite board and the internal connections are spaced so as to be as far apart as possible. A bakelite cover is also fitted above the ebonite board for protection of the instrument from light and dirt. The knobs operating the moving parts project through holes in this cover, which also carries the graduation marks.]

Student's Potentiometer

Crompton's potentiometer is a comparatively costly instrument. Moreover, it requires skill for its proper operation and careful handling. For this reason, less expensive and easy-to-operate student's potentiometers are available in various patterns, one of which is depicted in fig-63.

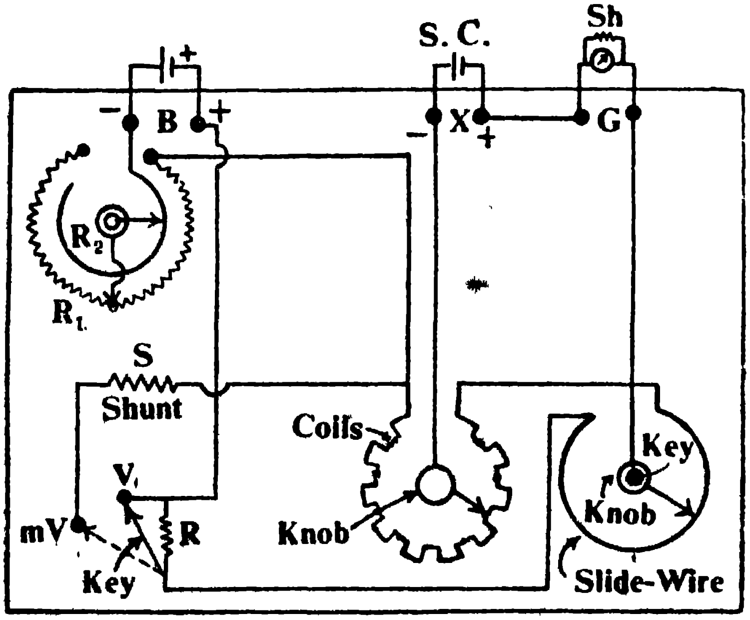

Fig. 63
Student's potentiometer

It consists of a number of coils of manganin wire arranged in the form of a circle and connected in series with a manganin slide-wire also in a circle form. The wire can be rotated with the help of a knob, at the centre of which is provided a key by depressing which contact at any point on the slide-wire is affected, the corresponding reading being given by a circular graduated scale. R_1 and R_2 are two rheostats which are put in series with the main battery circuit (marked B in the figure). R_1 being for coarse adjustment while R_2 is for finer one. The source of unknown E.M.F. is connected at X with the polarity as marked, and the galvanometer is connected at G.

Provision is made in the instrument to read directly either volts or millivolts. For this purpose, a key is provided in the left, which normally makes contact with a stud marked V, meaning thereby that under this condition the scale provided with the instrument shall indicate volts. When the instrument is desired to read millivolts, the key is swung towards the left, as shown by the dotted line, and now it makes contact with the stud marked mV (meaning millivolts). This operation results in including a resistance R in the battery circuit, and a shunt is put in parallel with the potentiometer wire with the result that the instrument standardised to read volts can give readings in millivolts by shifting this key only.

[Note—It is easy to see that the resistance R should be equal to 999 times the resistance of the coils and the slide-wire combined. This process, however, results in reducing the current flowing in the slide-wire. Hence automatically the shunt resistance is brought in the circuit, which keeps the current through the main battery circuit constant.

The resistance of the shunt required can be easily worked out as follows :—

Let the resistance of the potentiometer wire with the coils in series with it be x ohms, then the total resistance with the inclusion of R (= 999x ohms) is equal to 1000 x ohms. If the shunt resistance be S, then the equivaledt resistance of the combination is $\frac{1000\,x.\,S}{1000\,x + S}$. In order to keep the battery current unaltered, this equivalent resistance must be equal to x. Thus

$$\frac{1000\,x.\,S}{1000\,x + S} = x$$

Hence $$S = \frac{1000\,x}{999} \text{ ohms.}$$

In this way a resistance of requisite magnitude is inserted for the shunt.]

EXPERIMENT—31

Objects. To calibrate a voltmeter (of a given range) with a potentiometer.

Apparatus Required. A potentiometer, the given voltmeter, two storage batteries, two rheostats, a standard cell (cadmium cell, if available, otherwise a Daniell cell), a Weston galvanometer, two one-way keys, one two-way key, and connection wires.

Formula Employed. The error in the voltmeter reading is given by—

$$V' - V = V' - \frac{E.l_2}{l_1}$$

where V' = P. D. between two points read by the voltmeter.
V = P. D. between the same two points as read by the potentiometer.
E = E.M F of the standard cell *
l_1 = Length of the potentiometer wire corresponding to the E. M. F. of the standard cell.
l_2 = Length of the potentiometer wire corresponding to the P. D. (V) measured by the potentiometer.

[**Note.** E/l_1 gives the potential gradient along the wire]

PRINCIPLE AND THEORY OF THE EXPERIMENT

The calibration of a voltmeter with a potentiometer means the measurement of potential difference between any two points by means of the voltmeter and the measurement of the same potential difference between the same two points by a potentiometer, and then to examine how far the two values agree. Potentiometer being by far the more accurate instrument, the error in the voltmeter reading can be easily determined.

For this purpose, the potentiometer wire is calibrated, in the usual way, with the help of a standard cell (not shown in fig.-64). Let the length of the potentiometer wire for no deflection in the galvanometer be l_1. If E be the E. M. F. of the standard cell

$$E = k\, l_1$$

where k is the potential gradient along the potentiometer wire.

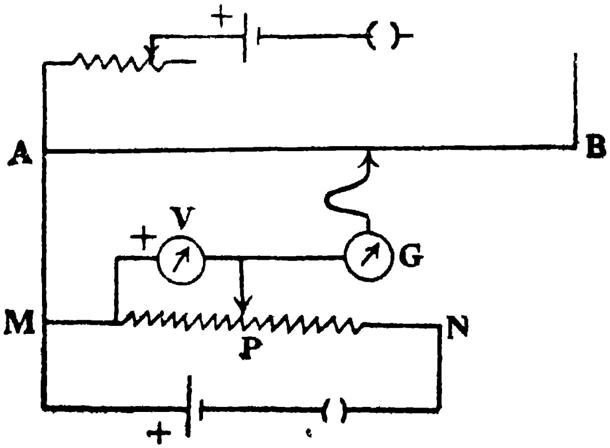

Fig. 64
Principle of calibration of a voltmeter

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* The E. M. F. of the Daniell cell (which is often used as a standard cell for ordinary laboratory practice) is 1 08 volts.

Now let an auxiliary circuit be set up as shown in fig.-64, in which a constant current is maintained through a rheostat MN. The potential difference between M and the variable point P is measured with the help of the potentiometer. Let the null-point in the galvanometer be obtained on the potentiometer wire at a length l_2. Then the potential difference V between the points M and P is given by

$$V = k\, l_2 = E l_2 / l_1.$$

If the potential difference between the same two points M and P as measured by the voltmeter to be calibrated be V′ the error in the voltmeter reading is (V′—V).

In this way by shifting the point P and measuring the potential differences between M and the new positions of P with the help of the voltmeter as well as the potentiometer, the voltmeter can be calibrated in the required range and a calibration curve of the voltmeter can be drawn between the observed voltmeter readings (V′) and the errors (V′—V).

Method

(i) Set up the apparatus as shown in fig.-65 (a). Connect the shortage battery E_1, fully charged and of fairly large capacity (so that it gives practically a constant current through the potentiometer wire) to the ends A and B of the potentiometer wire through two rheostats* R_1 and R_2 and a plug-key K_1.

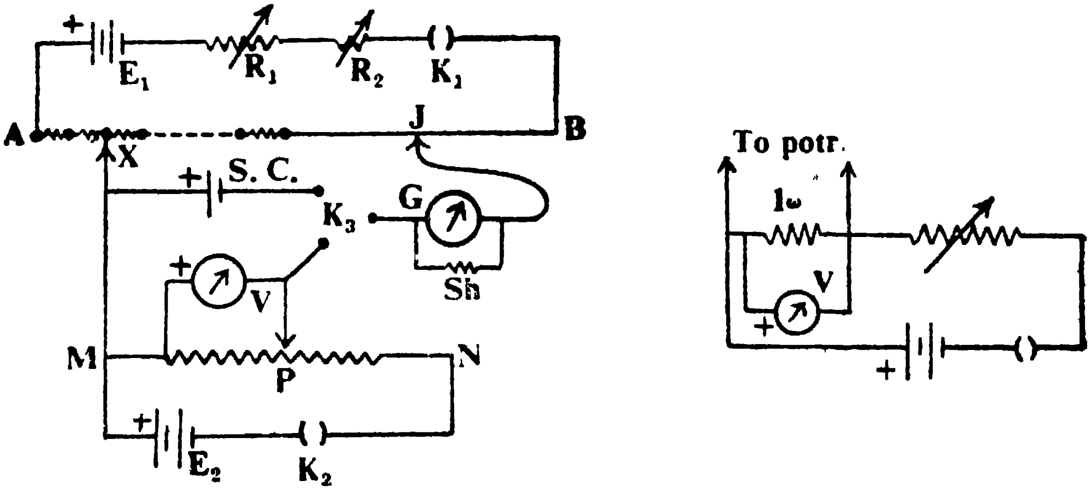

Fig. 65
Connections for calibration of a voltmeter

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* Instead of two rheostats, only one may be employed, but with the former there is greater facility in adjusting current through the potentiometer wire, R_1 may be of the order, say 200 ohms and R_2 of 10 ohms, the former is used for rough adjustment while the latter for finer one. The finer adjustment is not easily attained with a single rheostat.

Prepare an auxiliary circuit* as shown below the potentiometer wire (see fig.–65a). E_2 is a second storage battery, also giving a constant current, connected through K_2, to the fixed terminals M and N of a rheostat. The variable contact P is connected as shown.

S. C. is a standard cell (say, a Daniell cell) whose positive end, as well as the higher potential terminal M of the rheostat, are connected *towards* the higher potential end A of the potentiometer. The negative pole of the standard cell, as also the variable point P, are connected through the two-way key K_3 and the shunted galvanometer to the jockey J sliding along the potentiometer wire.

(ii) Close the key K_1 of the main circuit and connect the negative terminal of the standard cell by means of the two-way key (K_3) to the galvanometer. Place the contact-maker X at one end A of the potentiometer wire and place the jockey at 80 on the slide-wire†. Adjust the rheostats (R_1 and R_2) in the main circuit till there is no deflection in the galvanometer. By this procedure, we obtain a potential gradient of 1 millivolt per division along the potentiometer wire. Thus the instrument is made direct-reading‡ and the calculations are very much simplified.

(iii) Next connect the variable point P to the jockey and determine the total length (l_2) of the potentiometer wire when the balance-point is obtained on the wire. Note down the reading (V)' of the voltmeter. Calculate the error with the help of the formula given above.

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* The auxiliary circuit may be slightly modified, if desired, to one as shown in fig.–65 (b). It includes in addition one fixed resistance of, say, one ohm. Thus, in this case, the potential difference is measured between the ends of this resistance. This P. D. can be varied by operating the rheostat included in the circuit for this purpose. The fundamental principle in the two arrangements is essentially the same, the only advantage of the latter arrangement is that the connections are less confusing. The superiority of the former method lies in the fact that very little current is drawn from the battery E_2 throughout the entire experiment.

† This length of 1080 divs. of the potentiometer wire corresponds to l_1 of the formula given above.

‡ If a ten-wire potentiometer is used, the standardisation can be done at 540 divs. of the wire. In this case the potentiometer shall read 2 millivolts per division.

(iv) By altering the position of the variable point P, continue the above process till the entire range of the voltmeter is covered in suitable steps.*

(v) Now plot a graph† between the observed values (V′) of the voltmeter, represented on the x-axis, and the errors (V′ − V), represented on the y-axis.

Observations

[A] *Readings for the calibration of the potentiometer wire.*

Length of the potentiometer wire corresponding to the E. M. F. of the standard cell			Remarks
No. of coils	Length of the slide wire	Equivalent length (l_1)	(1) E. M. F. of the standard cell (E) = ...‡ volt
			(2) Potential gradient (E/l_1) = ... volt/cm.

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* The calibration of the potentiometer wire should be checked now and then to see that the potential gradient established in the beginning remains unaltered. For this purpose, bring the standard cell in the circuit, keep the sliding contact-makers X and J *exactly at the same positions as in the first calibration process*, and test whether there is no deflection in the galvanometer. If the balance point has been disturbed, adjust the rheostat R_2 so that the null-point is again obtained at the same position.

† Join the consecutive points on the graph by straight lines. Since the voltmeter range has been divided in fairly small intervals, the relation between errors and the corresponding voltmeter readings will be more or less linear.

‡ Take the E. M. F. of the standard cell 1·0184 volt for the cadmium cell, or 1·08 volt for the Daniell cell.

[B] *Readings for the calibration of the voltmeter.*

S. No.	Length of the potr. wire corresponding to the P. D. between M and P			P. D. as read by the potentiometer (V)	P. D. as read by the voltmeter (V′)	Error* in the reading of the voltmeter (V′ − V)
	No. of coils	Length of the slide wire	Equivalent length			

Calculations Potential gradient, k = ... volt/cm.

Set I.

$$V = kl_2 = \ldots \text{ volt.}$$

[**Note**—Make similar calculations for the remaining readings.]

Result—The calibration curve (obtained by plotting the errors against the voltmeter readings) for the given voltmeter is attached herewith.

Precautions and Sources of Error

(1) The sucess of the experiment depends upon the constancy of the E. M. F.'s of the two storage batteries. They should have large capacity and should be fully charged. *Their voltages should be ascertained before inserting them in the circuit.*

(2) The ends of the connection wires should be cleaned and they should be firmly secured between the binding terminals. The wires connected to the higher potential points should all be led *towards* the same end of the potentiometer wire.

(3) The potential difference at the ends of the potentiometer wire should be greater than the maximum potential difference to be measured during the experiment. The rheostat in the main circuit should be so adjusted that this condition is fulfilled.

(4) In order to avoid unnecessary heating in different parts of the circuit two plug-keys should be used—one in the main circuit and the other in the auxiliary one.

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* **Prefix +ve or −ve sign before each value of the error.**

(5) Change over from the standard cell to the auxiliary circuit should be done quickly with the help of the two-way key. Moreover, the calibration of the wire should be checked, now and then, during the course of the experiment by including the standard cell in the circuit. If the null-point with the standard cell is found to have shifted, it should be restored to the same position by adjusting the rheostat of low value in the main circuit.

(6) The contact of the jockey with the slide-wire should be mometary, and the jockey should not be moved along the wire while it is being pressed, otherwise the wire will be unevenly worn out and the uniformity of the wire will be impaired.

(7) During the early stages of locating the balance point the galvanometer should be kept shunted with a low resistance wire, so that excessive currents are avoided through the galvanometer. Exact position of the null-point should be determined with the shunt removed

(8) The potential gradient along the wire shall be uniform provided the wire is of constant thickness throughout its entire length. Hence the potentiometer should have its slide-wire of uniform thickness. If the potentiometer employed is a ten-wire potentiometer, the non-uniformity of the wire shall constitute a source of error.

EXPERIMENT—32

Object—To calibrate an ammeter (of a given range) with the help of a potentiometer.

Apparatus Required—A potentiometer, the given ammeter, two storage batteries, suitable rheostats, standard cell, Weston galvanometer, a standard one-ohm resistance, two-way key, single-way plug key, connection wires.

Formula Employed—Let the potential difference at the ends of the one-ohm coil be V, and let the null-point on the potentiometer correspond to a length l_1 of the wire then the current I flowing through the coil is given by.

$$I = \frac{V}{R} = V = k\, l_1$$

The potential gradient k is given by : $k = E/l$, where E is the E. M. F. of the standard cell and l is the corresponding balancing length on the wire. Thus

$$I = \frac{E}{l} \cdot l_1$$

The error of the ammeter $= I' - I$, where I' is the reading of the ammeter.

PRINCIPLE AND THEORY OF THE EXPERIMENT

The calibration of an ammeter with a potentiometer means literally the measurement of a current flowing in a circuit by an ammeter and its measurement with a potentiometer, and then to examine how far the two values agree. Potentiometer being a more accurate current-measurer, the error in the ammeter reading can be easily determined.

As a matter of fact, a potentiometer can accurately measure potential differences only ; it can be made to measure currents in an indirect manner. For this purpose let us examine fig.–66. AB is the potentiometer wire which has been previously calibrated with a standard cell. If E be the E. M. F. of the standard cell, which is balanced on a length l of the wire then the potential gradient, $k = E/l$, is known.

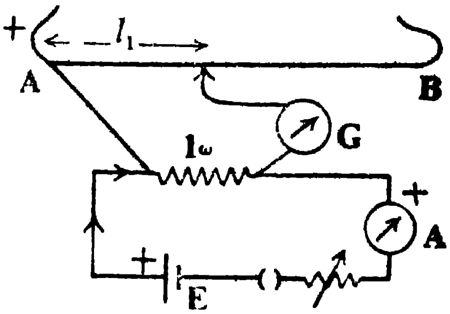

Fig. 66
Principle of calibration
of an ammeter

Now an auxiliary circuit (as shown in the figure) is set up. In this circuit a standard one ohm* coil is also included. Let the current flowing through the coil be I, then, by Ohm's law a potential difference $V (= IR = I \times I = I)$ is created at its ends. This can be balanced on the potentiometer wire If l_1 is the balancing length of the wire, then

$$V (= I) = kl_1 = \frac{E}{l} \; l_1$$

Thus I is calculated. In this way the potentiometer becomes a current-measurer.

The same current is measured by the ammeter A included in the circuit. If it records a current I, the error in the instrument is equal to (I′—I).

In this way by operating a rheostat, also included in the auxiliary circuit the value of the current can be varied and the corresponding potential differences produced at the ends of the one-ohm coil can be measured. In this way the entire range of the ammeter can be calibrated, and a curve between the errors (represented along the y-axis) and the observed readings of the ammeter (represented along the x-axis) can be drawn.

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* A resistance of 1 ohm is purposely employed. It eliminates calculation work.

Method

(i) Set up the apparatus as shown below (Fig -67)—connect the storage battery E_1 fully charged and of fairly large capacity (so that it gives a constant current through the potentiometer wire), to the ends A and B of the potentiometer wire through two rheostats* R_1 and R_2 and a plug-key K_1.

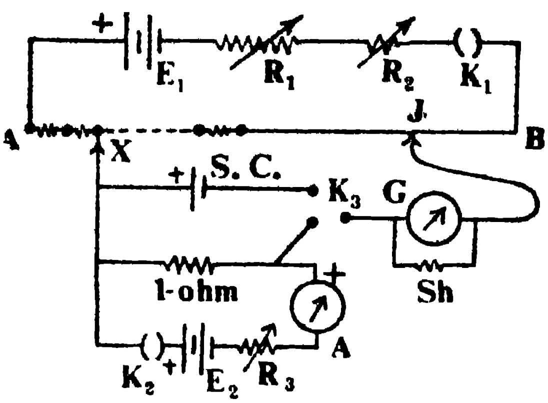

Fig. 67
Connections for the calibration of an ammeter

Prepare an auxiliary circuit as shown below AB. E_2 is a second storage battery, also giving a constant current connected through K_2, the rheostat R_3, the ammeter A to a standard 1-ohm resistance coil. The higher potential end of the coil is connected to the contact maker X, and the lower potential terminal to the two-way key as shown in the figure.

S. C. is a standard cell whose positive pole also is connected † to the contact maker X The negative pole is connected to the two-way key. This (or the lower potential terminal coming from the standard coil) can be connected through the shunted galvanometer to the jockey sliding over the potentiometer wire.

(ii) Close the key K_1 of the main circuit and connect the negative terminal of the standard cell by means of the two way key (K_3) to the galvanometer. Place the contact maker X at the end A of the potentiometer wire and place the jockey (J) at the division marked 80 on the slide-wire‡. Adjust the rheostats (R_1 and R_2) in the main circuit till there is no deflection in the galvanometer. By this procedure we obtain a potential gradient of 1 millivolt per division along the potentiometer wire. Thus the

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* Instead of two rheostats, only one may be employed, but with the former arrangement the current flowing through the potentiometer can be adjusted with greater facility. R_1 may be of the order, say, 200 ohms and R_2 of 10 ohms; the former is manipulated for rough adjustment while the latter for finer one. The finer adjustment is not easily attained with a single rheostat.

† All the higher potentials terminals should be connected *towards* A, which is joined to the positive pole of the battery included in the main circuit.

‡ This length of 1080 divs. of the potentiometer wire corresponds to *l* of the formula given above.

potentiometer is made direct-reading* and the calculations are very much simplified.

(iii) Next connect the lower potential end of the one-ohm, coil to the jockey and determine the total length (l_1) of the potentiometer wire when the balance point is obtained on the wire Note down the reading of the ammeter. Calculate its error with the help of the formula given above.

(iv) By operating the rheostat included in the auxiliary circuit vary the current in suitable steps, and continue the above process till the ammeter is calibrated in its entire range†.

(v) Now plot a graph‡ between the observed values (I′) of the ammeter, represented on the x-axis, and the errors (I′—I), represented on the y-axis.

Observations

[A] *Readings for the calibration of the potentiometer wire.*

Length of the potentiometer wire corresponding to the E. M. F. of the standard cell			Remarks
No. of coils	Length of the slide wire	Equivalent length (l)	(1) E. M. F. of the standard cell (E) = ... **volt
			(2) Potential gradient (E/l) = ... volt/cm.

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* If a ten-wire potentiometer is used, the standardisation can be done at 540 divs. of the wire. In this case the potentiometer shall read 2 millivolts per division.

† The calibration of the potentiometer wire should be checked now and then to see that the potential gradient established in the beginning remains unaltered. For this purpose, bring the standard cell in circuit, keep the sliding contact makers exactly at the same positions as in the first calibration process, and test whether there is no deflection in the galvanometer. If the balance point has been disturbed, adjust the rheostat R_2 so that the null-point is again had at the same position.

‡ Join the consecutive points on the graph by straight lines. Since the ammeter range has been broken up in steps of fairly small values, the relation between errors and the corresponding ammeter readings during these intervals will be more or less linear.

** Take the E M. F. of the standard cell 1·0184 volt for the cadmium cell, or 1·08 volt for the Daniell cell.

[**B**] *Readings for the calibration of the ammeter.*

S. No	Length of the potentiometer wire corresponding to the P. D. across the standard coil			P. D. across the 1-ohm coil	Accurate value of the current (I)	Ammeter reading (I′)	Error* (I′ − I)
	No. of coils	Length of the slide wire	Equivalent length				

Calculations Potential gradient, $k =$ ... volt/cm.

Set I

$V_1 = k\ l_1 =$ ... volt.

Hence $I_1 = V_1 =$ ... amp.

[**Note**—Make similar calculations for the remaining readings.]

Result—The calibration curve (obtained by plotting the errors against the ammeter readings) for the given ammeter is attached herewith.

Precautions and Sources of Error.

(1) The success of the experiment depends on the constancy of the E. M. F.'s of the two storage batteries. They should have large capacity and should be fully charged. *Their voltage should be as certained before inserting them in the circuit.*

(2) The ends of the connection wires should be cleaned and they should be firmly secured between the binding terminals. The wires connected to the higher potential terminals should all be led towards the same end of the potentiometer wire.

(3) The potential difference at the ends of the potentiometer wire should be greater than the maximum potential difference to be

---

Prefix +ve or −ve sign before the value of each error.

measured during the experiment. The rheostat in the main circuit should be so adjusted that this condition is fulfilled.

(4) In order to avoid unnecessary heating in different parts of the circuit two plug-keys should be used—one in the main circuit and the other in the auxiliary one.

(5) The ammeter should be connected in series in the circuit with the positively marked terminal to the higher potential point.

(6) Change over from the standard cell to the auxiliary circuit should be done quickly with the help of the two-way key. Moreover, the calibration of the wire should be checked, now and then, during the course of the experiment by including the standard cell in the circuit. If the null-point with the standard cell is found to have shifted, it should be restored to its initial position by adjusting the rheostat of low value in the main circuit.

(7) The contact of the jockey with the slide-wire should be momentary, and the jockey should not be moved along the wire while it is being pressed, otherwise the wire will be unevenly worn out and the uniformity of the wire will be impaired.

(8) During the early stages of locating the balance-point the galvanometer should be kept shunted with a low resistance wire. so that excessive currents are avoided through the galvanometer. Exact position of the null-point should be determined with the shunt removed.

(9) The potential gradient along the wire shall be uniform provided the wire is of constant thickness throughout its entire length. Hence the potentiometer should have its slide-wire of uniform diameter.

(10) The accurate measurement of current with the potentiometer depends on the accurate knowledge of the value of the standard resistance. If ordinary 1-ohm coil is employed, its value is not absolutely reliable, and the calibration of the ammeter shall be imperfect. For this purpose a standard resistance provided with separate current and potential terminals should be used.

EXPERIMENT—33

Object. To determine the internal resistance of a Leclanche cell with the help of a potentiometer.

Apparatus Required. Leclanche cell, a 10-wire potentiometer, storage battery, Weston galvanometer, rheostat,-resistance box, a high resistance (of the order of 10,000 ohms), plug key, tapping key, and connection wires.

Formula Employed. The internal resistance (r) of the cell is calculated with the help of the following formula—

$$r = \left(\frac{l_1}{l_2} - 1 \right) R$$

where l_1 = Balancing length on the potentiometer wire when the Leclanche cell is on open circuit, i. e., the length corresponding to the E. M. F. of the cell.

l_2 = Balancing length on the potentiometer wire when the cell is in closed circuit, i. e., when a current is drawn from the cell.

R Resistance through which current from the Leclanche cell is drawn.

PRINCIPLE AND THEORY OF THE EXPERIMENT

When the poles of a cell are connected by an external resistance, a current begins to flow in the circuit. In the external circuit the current flows from the positive pole to the negative pole, while inside the cell the current is driven from the negative pole to the positive pole. During the passage of the current inside the cell the electrolyte offers some resistance to the flow of the current. This resistance offered by the cell is called its internal resistance and is denoted by the symbol r. The internal resistance of a cell depends on the area of the plates immersed in the electrolyte, the distance between them, the nature of the electrolyte, and also on the strength of the current which pases through the circuit. For very weak currents the internal resistance is practically independent of the strength of the current.

The internal resistance of a primary cell* can be determined by a potentiometer. Let AB represent a potentiometer wire in which a constant current is flowing A is at a higher potential than B. E is the Leclanche cell whose internal resistance is to be determined. The positive pole of this cell is connected to A and the negative pole through the galvanometer G to the jockey J which slides along the wire. With key K open let the cell be balanced and let l_1 be the corresponding length of the wire. Now, since the cell is on open circuit, the potential difference (V) between the points A and J balances the E. M. F. of the cell. Hence

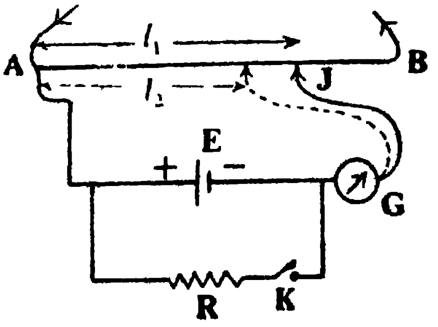

Fig. 68
Principle for the internal resistance of a cell.

$$E = V = kl_1 \quad \ldots \quad (1)$$

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* The potentiometer method is unsuitable for determining the internal resistance of a secondary cell or any other cell whose resistance is very low. With such a cell a large current has to be drawn for producing a measurable fall of potential. Such excessive currents can damage the cell.

where k is the potential gradient along the wire and E is the E.M.F. of the Leolanche cell.

Let the cell be now short-circuited by a resistance R by depressing the key K. A current is drawn from the cell and consequently the P. D. (V_1) now existing between its poles is less than the E.M.F. The balancing point consequently shifts towards A. Let the new balancing length of the potentiometer wire be l_2, then

$$V_1 = kl_2 \qquad \ldots \qquad (2)$$

Hence

$$\frac{E}{V_1} = \frac{l_1}{l_2} \qquad \ldots \qquad (3)$$

Now applying Ohm's law to the circuit consisting of the cell and the external resistance R we have

$$\text{Current} = \frac{E}{R + r} = \frac{V_1}{R} \qquad \ldots \qquad (4)$$

where r is the internal resistance of the cell. From (4) we have

$$\frac{R + r}{r} = \frac{E}{V_1}$$

or

$$r = (E/V_1 - 1)\,R \qquad \ldots \qquad (5)$$

Substituting the value of E/V_1 from (3) in (5) we have

$$r = (l_1/l_2 - 1)\,R \qquad \ldots \qquad (6)$$

This is the required equation to determine the value of r.

Method

(i) Set up the apparatus as shown below—

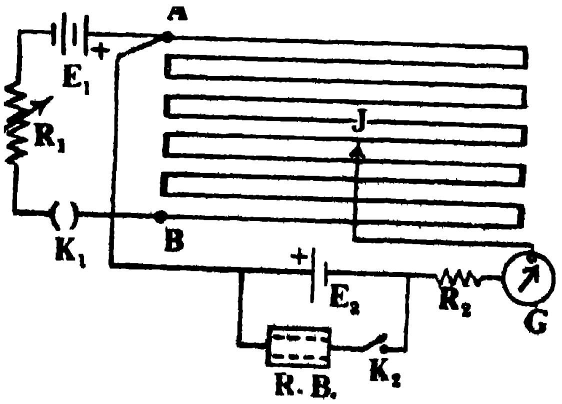

Fig. 69
Connections for the internal resistance of a cell

Connect the storage battery E_1, fully charged and of fairly large capacity (so that it gives practically a constant current through the potentiometer wire) to the ends of the potentiometer wire through a rheostat R_1 and a plug-key K_1.

Connect the positive pole of the Leclanche cell E_2 *to the point A where the positive pole af the battery is also connected.* Connect the negative pole of E_2 through a high resistance* R_2, the galvanometer G to the jockey J sliding over the potentiometer wire. Connect a resistance box and a tapping key K_2 across the cell.

(ii) Close the key K_1 and bring the jockey near the end A. Press the jockey and note the deflection in the galvanometer. Now bring the jockey on the last wire near the end B and again note the deflection after pressing the jockey here. If the connections are correct the two deflections must be in opposite directions. If it is not so, the potential difference between the ends of the potentiometer wire is less than the E M.F. of the Leclanche cell In that case reduce the resistance in the main circuit by operating the rheostat R_1 and adjust its value till the balance point is obtained roughly on the last wire. Determine the exact position of the null-point by removing R_2 connected in series with the galvanometer. Open K_1 and measure the length of the wire from A to the point where the null-point has been obtained. This is l_1 of the formula given above.

(iii) Introduce a suitable resistance in the resistance box. Press the tapping key K_2 and obtain as before the new position of the exact balance point by shifting the jockey and determine the value of l_2.

(iv) Repeat the experiment with different values of R introduced in the resistance box, taking observations alternately with the Leclanche cell on open and closed circuit. Finally calculate the internal resistance of the cell for each set of observation separately.

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* The high resistance R_2 may be of the order of 10,000 ohms. It has a special function to perform. It prevents the flow of excessive currents through the galvanometer, as well as it minimises the polarisation in the cell. This method suffers from all those defects which arise due to the polarisation taking place in the cell, hence polarisation has to be reduced as far as possible.

This resistance is used only upto the approximate balancing point. For locating the exact null-point this is removed from the circuit.

Observations

S. No.	Length of the potentiometer wire with the tapping key		Resistance introduced in the resistance box (R)	Internal resistance of the cell (r)
	open (l_1)	closed (l_2)		

Calculations

Set I

$$r_1 = (l_1/l_2 - 1)\ R$$
$$= \ldots\ \ldots\ \ldots \text{ ohm.}$$

[**Note.** Calculate similarly for other sets also.]

Result. From the values obtained for the internal resistance of the Leclanche cell it is found that it varies with the current drawn from the cell and its value lies between ...ohms and ...ohms.

Precautions and Sources of Error

(1) The ends of the connection wires should be carefully cleaned and they should be firmly secured between the binding terminals.

(2) The positive terminals of the battery as well as the Leclanche cell should be connected to the same end of the potentiometer wire.

(3) The storage battery should be fully charged and should have fairly large capacity so that it gives a practically constant current through the potentiometer wire and consequently the potential gradient also remains constant throughout the experiment.

(4) The rheostat in the main circuit should be so adjusted that the balance point with the Leclanche cell on the open circuit is obtained on the last wire. In this way maximum sensitivity of the instrument is utilised.

(5) A high resistance should be connected in series with the galvanometer, which should be disconnected when the approximate null-point is obtained.

(6) The jockey should be momentarily pressed on the potentiometer wire and it should not be moved along the wire when it is pressed, otherwise the uniformity of the wire shall be impaired.

(7) The unecessary heating of the potentiometer wire should be avoided by keeping the key in the moin circuit closed only when readings are taken.

(8) A tapping key should be inserted in the resistance box circuit. This should be pressed momentarily* when the null point is being, sought, and released again as soon as the jockey is raised from the wire for adjusting to a fresh position along the potentiometer wire.

(9) Apart from the polarisation affect on the internal resistance, the result shall also be adversely influenced by the non-uniformity of the potentiometer wire, which is highly probable in such a long wire. A non-uniform wire will not have a constant potential gradient along its entire length.

EXPERIMENT—34

Object. To compare two low resistances by means of a potentiometer.

Apparatus Required. Two low resistances, potentiometer, two storage batteries, two rheostats, Weston galvanometer, a six-terminal key (or a Pohl's commutator), two plug keys, and connection wire.

Formula Employed : $\frac{R_1}{R_2} = \frac{l_1}{l_2}$

where R_1, R_2, = The two resistances to be compared.

l_1, l_2 = Corresponding lengths of the potentiometer wire when balance points are obtained.

PRINCIPLE AND THEORY OF THE EXPERIMENT

If the two resistances to be compared are connected in series and a study current is allowed to flow through them, then by Ohm's law, the potential differences across them will be proportional to their resistances Now these potential differences can be accurately compared with a potentiometer, hence the resistances are thereby compared.

---

* If the tapping key is kept pressed for an appreciable time, the cell shall be polarised, and a gradual drift in the balance point shall be observed.

Let us refer to fig.-70, in which AB is the potentiometer wire carrying a steady current in the direction A to B so that A is at a higher potential than B. Let k be the potential gradient along the wire.

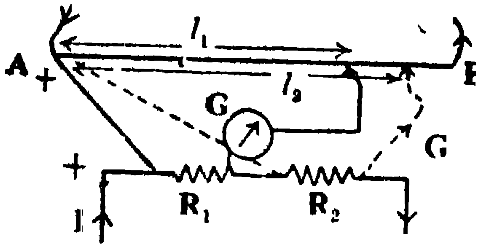

Fig 70
Principle for comparison of two resistances

Now R_1 and R_2 are the two resistances to be compared. Let them form part of an auxiliary circuit in which a steady current I is flowing. Let the higher potential terminal of R_1 be connected to A (*i e* . the higher potential end of the wire), and the lower potential terminal to the jockey. Let l_1 be the length of the potentiometer wire when a null-point is obtained. The potential difference V_1 at the ends of R_1 is given by,

$$V_1 = k\, l_1$$

But by Ohm's law

$$V_1 = I\, R_1$$

Hence

$$I\, R_1 = k\, l_1 \qquad \dots \quad (1)$$

Let R_1 be disconnected from the potentiometer wire, and let R_2 be now connected to A and the jockey, as shown by dotted lines. Let the potential difference V_2 across this resistance be balanced on a length l_2 of the potentiometer wire. Then

$$V_2 = k\, l_2$$

or

$$I\, R_2 = k\, l_2 \qquad \dots \quad (2)$$

From (1) and (2) we have

$$\frac{R_1}{R_2} = \frac{l_1}{l_2} \qquad \dots \quad (3)$$

Method

(i) Set up the apparatus as shown in fig.-71. Connect the storage battery* E_1 to the ends A and B of the potentiometer wire through a rheostat Rh_1 and a plug-key K_1. The end A is connected to the positive pole of the battery so that the potential at A is higher than that at B.

---

* For the accuracy of the result it is essential that the potential gradient existent along the wire is constant throughout the experiment. It will be nearly so if the battery supplies a constant current. For this purpose a battery *fully charged* and of fairly *large capacity* should be employed.

Prepare an auxiliary circuit as shown below the potentiometer wire AB. E_2 is a second battery, also giving a constant current,

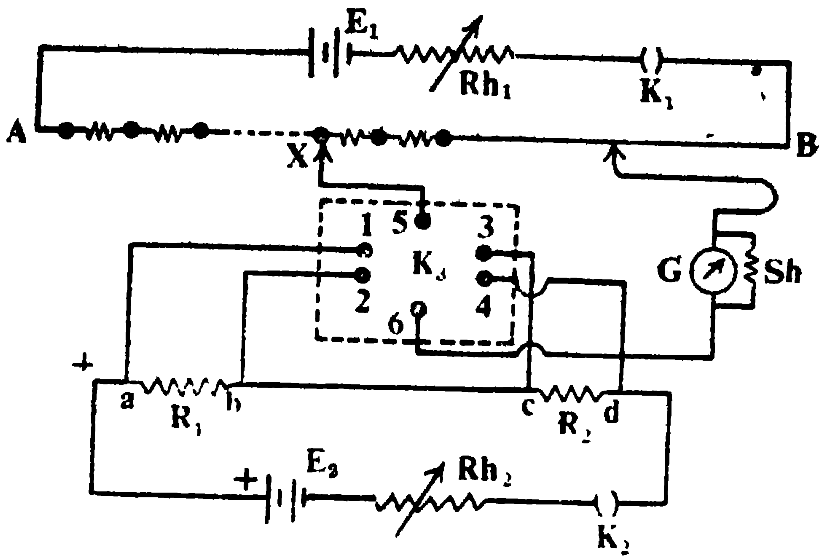

Fig. 71
Connections for the comparison of two resistances

connected to the two given resistances R_1 and R_2 through a rheostat Rh_2 and K_2.

K_3 is a six-way key*, whose terminals are numbered in the figure. Connect the higher potential terminal 'a' (marked +) of R_1 to terminal No 1, and lower potential terminal b to No. 2. Similarly connect c (higher potential terminal of R_2) to No. 3 and d to No 4. Connect terminal No. 5 to the contact maker X and No. 6 to the jockey J through the shunted galvanometer G.

(ii) Before doing the actual experiment secure first maximum sensitiveness for the potentiometer, *i. e., the potential gradient of the wire should be small, and at the same time the P. D. at the ends A and B should be greater than the P. D. to be balanced on the wire*

[**Note.** This can be easily accomplished as follows :

First of all estimate (roughly) which of the two resistances is greater, since if the P. D. across its ends can be balanced, that

---

* By this arrangement the two resistances R_1 and R_2 can be successively brought in circuit. When R_1 is used by connecting 5 to 1, and 6 to 2, the resistance R_2 is completely cut off from the circuit. Next time when R_2 is brought in circuit by connecting 5 to 3, and 6 to 4, the resistance R_1 is completely cut off from the main circuit. *A two-way key should not be employed* in place of this key, as in this case a resistance *is not completely cut off* from the potentiometer circuit, and consequently the positions of the null-points are erroneous.

across the smaller one will obviously be balanced, but the reverse may not always be true. For this purpose, adjust the rheostat Rh$_2$ to a low value. Determine approximately the balance point with R$_1$, and then with R$_2$. The equivalent lengths of the wire obtained in the two cases will indicate which resistance is greater. Let us suppose that R$_1$ is greater than R$_2$. Now switch this resistance R$_1$ to the potentiometer circuit. Place the contact maker X to the last stud of the coils and place the jockey on the wire. By adjusting the rheostat Rh$_1$ of the main circuit obtain a null-point on the slide wire. This procedure adjusts the P. D between A and B to be greater than that across the resistances R$_1$ and R$_2$, and at the same time secures maximum sensitivity of the potentiometer.]

(iii) Now obtain the exact balance points with R$_1$ and then with R$_2$, and note the corresponding lengths l_1 and l_2 of the wire.

(iv) Next **increase** the resistance in the rheostat Rh$_2$ and obtain the new values of l_1 and l_2. In this way, by slightly increasing the resistance in Rh$_2$ each time, take several readings, and calculate l_1/l_2 in each case. From this obtain the mean value of R$_1$/R$_2$.

Observations

S. No.	Length of the potentiometer wire corresponding to the Potential Difference						Ratio of the two resistances
	Across the first resistance (R$_1$)			Across the second resistance (R$_2$)			
	No. of coils	Length of wire	Equivalent length (l_1)	No. of coils	Length of wire	Equivalent length (l_2)	l_1/l_2
						Mean	

Calculations

Set I

$$\frac{R_1}{R_2} = \frac{l_1}{l_2} = \dots\dots$$

[**Note.** Calculate this ratio for each set separately and take the mean value.]

Result. The ratio of the two given resistances = ...

Precautions and Sources of Error

(1) The ends of the connection wires should be carefully cleaned and they should be firmly secured in the binding terminals. All the higher potential terminals should be led towards A.

(2) The P. D. between the ends A and B should be greater than the potential difference across the given resistances, which have to be balanced on the wire.

(3) The potential gradient of the potentiometer wire should remain constant throughout the experiment. To attain this, the battery in the main circuit should be fully charged and it should have a fairly large capacity. Such a battery will supply a fairly constant current.

(4) The potentiometer should be so adjusted that maximum sensitivity is attained, i. e., with the maximum value of the P, D. to be balanced, the null-point should be obtained (by adjusting the rheostat in the main circuit) with all the coils included. This will ensure maximum sensitivity, and at the same time it will ensure that the P. D. between A and B is greater than V_1 (across R_1) and V_2 (across R_2).

(5) The storage battery used in the auxiliary circuit should also be fully charged and should have a fairly large capacity, so that it sends steady current through R_1 and R_2.

(6) To avoid unnecessary heating in different parts of the circuit, each circuit should have a plug-key which should be closed only when readings are being taken.

(7) A six-way key should be employed to include either R_1 or R_2 in the potentiometer circuit. Its connections should be carefully done. The charge-over from R_1 to R_2 should be done quickly, so that effects due to heating and variations in the batteries are minimised.

(8) The jockey should be pressed momentarily, and it should not be moved along the wire in a pressed state, otherwise by uneven rubbing the wire shall lose its uniformity.

(9) The approximate null-point should be obtained with the galvanometer shunted with a low resistance. The shunt should be removed when the exact null-point is to be located.

ADDITIONAL EXPERIMENTS

Expt.—34 (1)

Object. To determine the value of a low resistance with a potentiometer.

[**Note.** In the experiment just described the two low resistances to be compared are of the same order of magnitude. However, if the resistances to be compared are of the order, say, 1 ohm and 0.01 ohm, the following method is adopted.]

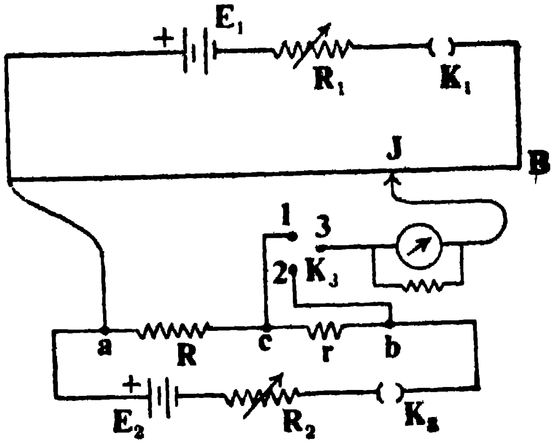

Fig. 72

Connections for the determination of a low resistance

The diagram is self-explanatory. r is the small resistance to be measured. In series with this is a resistance R of, say, 2 ohms. K_3 is a two-way key.

First balance the P. D. (v_1) between a and b i. e. at the ends of (R + r) by connecting 2 to 3. Let the balancing length of the potentiometer wire be l_1. Then balance the P. D. (v_2) between a and c (i. e , at the ends of R alone). Let the new balancing length of the wire be l_2. If I be the steady current flowing through R and r, we have.

$$\frac{V_1}{V_2} = \frac{I\,(R + r,}{I\,R} = \frac{l_1}{l_2}$$

where $r = (\,l_1/l_2 - 1\,)\,R$

In this way r can be determined.

[**Note.** (1) The above procedure can be adopted for determining the *specific resistance of copper.* For this purpose R replaces a standard resistance of, say, 0·1 or 0·01 ohm, and in place of r a copper wire is connected. In this case, the two resistances should have, for the sake of greater accuracy, four terminals each, two for leading the current in the conductor and two for measuring the potential difference. Then, as described just now, the resistance r of the copper wire is calculated with the help of the formula

$$r = (l_1/l_2 - 1\,)\,R$$

Knowing the length of the copper wire (only that length should be measured across which the P. D. has been measured), and the diameter, its specific resistance can be calculated.

(2) Using a decimal-ohm box in place of R and an ammeter in place of r, the *resistance of the ammeter* can be measured.

It should be added here that great accuracy can be attained in such determinations only when a very sensitive potentiometer, e. g. a Crompton's potentiometer is employed.]

EXPERIMENT—35

Object. To measure the thermo-electric e. m. f. generated in a copper-iron thermocouple for a known difference of temperature between its junctions.

Apparatus Required. A potentiometer, a standard cadmium cell, an accumulator, a copper-iron thermocouple, resistance box, rheostat, a sensitive galvanometer, a two-way key, plug-key, and connecting wires.

Description of the Apparatus

(a) **Potentiometer.** Since the magnitude of the thermo-electric e. m. f. is of the order of a few *millivolts**, the ordinary potentiometer method cannot be employed here. Such e. m f's can therefore be measured by a suitable modification of the ordinary method so as to produce a potential difference of the order of a microvolt across each cm. of the potentiometer wire which is small enough to admit of sufficiently accurate measurement.

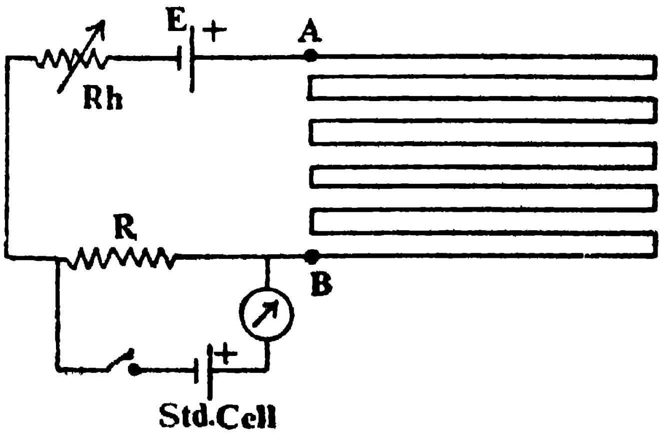

Fig. 73
Calibration of a potentiometer for direct reading

Let us take a ten-wire potentiometer such that its wire AB (fig.–73) is 1000 cm long and it has a resistance of 0·01 ohm per cm. If the resistance R has a value 1018 ohms, the potential difference across it will be exactly 1·018 volts when a current of 1 milli amp. flows through the circuit. Let the standard Weston cadmium cell, whose e. m. f. is 1 018 volts, be connected across R through a galvanometer and a key. Let the key be closed and the rheostat Rh be adjusted till the galvanometer shows no deflection. After this adjustment the wire AB carries a current of 1 milliamp. and hence it has a potential fall of $0{\cdot}01 \times 10^{-3} = 10 \times 10^{-6}$ (or 10 microvolts) per cm. of wire. The potentiometer can thus measure a smallest potential difference of 1 microvolt per mm and a maximum potential difference of 10 millivolt.

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* For instance, in a copper-iron thermo-couple the e. m. f. generated when the junctions are maintained at 0°C and 100°C is only 1·3 millivolt.

[Note—(i) If a standard cadmium cell is not available in the laboratory, a Daniell cell (e. m. f. = 1·08 volt) can be used. In that case the resistance R should have a value equal to 1080 ohms to give the above constants to the potentiometer.

(ii) If the millivolt potentiometer (or students' potentiometer is available in the laboratory, it can be employed for the measurement of the thermal e. m. f.'s, but the procedure adopted above is more instructive.]

(b) **Standard Cadmium Cell.** The Weston cadmium cell is shown in the accompanying figure. Two tubes are arranged as shown, each being provided with an external lead of platinum which is in contact with the bottom layers. These layers consist of pure mercury in one limb, and an amalgam of pure mercury and cadmium in the other. Above the pure mercury is a layer of a paste of mercurous sulphate. Above this and the cadmium amalgam is a layer in each tube of pure cadmium sulphate crystals. Finally, a layer of a saturated solution of pure cadmium sulphate occupies the upper parts of the two tubes.

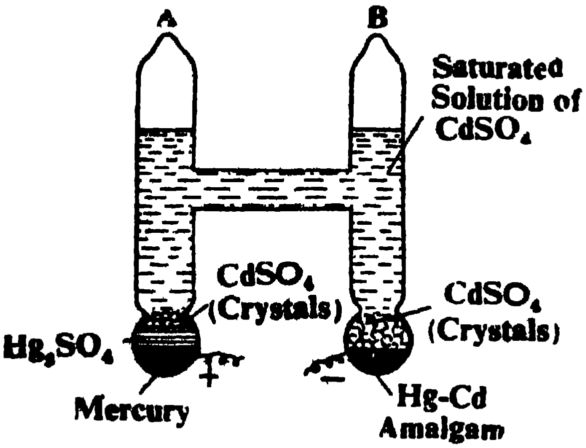

Fig. 74
Standard cadmium cell.

The following reactions take place in the cell :—

(i) $Cd = Cd^{++} + 2e$

(ii) $Cd^{++} + Cd\,SO_4 + Hg_2\,SO_4 = 2\,Cd\,SO_4 + Hg^+ + Hg^+$
(Depolariser)

(iii) $Hg^+ + Hg^+ - 2\,Hg + 2p$

where e and p represent respectively the elementary negative and positive charges.

The e. m. f. of the cell is constant at constant temperature. So that no current of any appreciable magnitude be drawn from the cell, the makers put a high resistance (of the order of 10,000 ohms) in series with it*. The International Conference on Electrical Units and Standards, 1908, adopted the following formula as giving most accurately the e. m. f. of the cell—

$E_t = 1{\cdot}0184 - 4{\cdot}06 \times 10^{-5}(t-20) - 9{\cdot}5 \times 10^{-7}(t-20)^2 + 10^{-8}(t-20)^3$ volt, where t is expressed in degrees centigrade.

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* This precaution is necessary, for if a standard cell supplies more than a small current it is subject to polarisation and the value of the e. m. f. becomes uncertain.

The temperature coefficient is therefore small.

[Note—There is another standard cell, known as Clark cell which is identical with the Weston cell except that the cadmium is replaced in this case by zinc, cadmium sulphate by zinc sulphate etc. The e. m. f. of this cell at 15°C is 1·4328 volt, but this cell has a large temperature coefficient—a fact which explains the more general use of the Weston cell.]

Formula Employed—The value of the thermo-electric e. m. f. (e) developed in a thermo-couple is obtained with the help of the following formula—

$$e = \frac{\rho E l}{R}$$

where ρ = Resistance per unit length of the potentiometer wire

E = E. M. F. of the standard cell

R = Resistance across which the standard cell is balanced

l = Length of the potentiometer wire when the thermo-electric e. m. f. is balanced on this.

PRINCIPLE AND THEORY OF THE EXPERIMENT

Seebeck discovered in 1821 that when two dissimilar metals (e. g., copper and iron) are joined and the two junctions are maintained at different temperatures, a current—known as thermo-electric current—flows round the circuit in a direction shown by arrows in fig.–75 (a). The value of the thermo-e.m. f. depends upon the metals constituting the thermo-couple and the difference of temperature between the two junctions. The thermo e. m. f. increases fig.–75 (b) as the temperature of the hot junction increases and reaches a maximum value at a characteristic temperature T_n known as the *neutral temperature*, beyond which the e. m. f. begins to decrease, till at a temperature T_i, called the *temperature of inversion*, the e. m. f. drops to zero and changes its sign*.

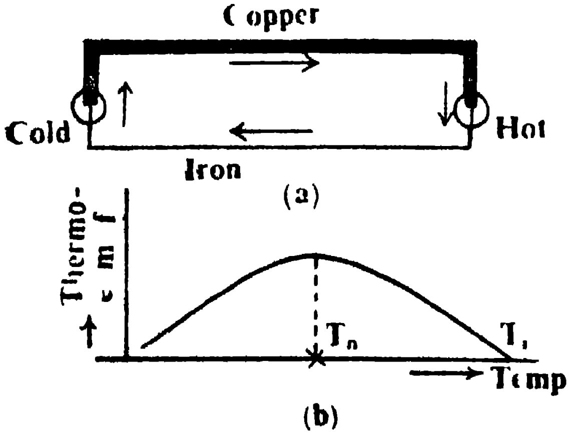

Fig. 75
Seebeck effect in copper iron thermo-couple.

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* This curve is a parabola and can be represented by an equation of the type $e_t = at + bt^2$ where a, b are constants for a particular couple.

Let the electric connections be made as shown in fig.-76, which is self-explanatory. Now, if the standard cell circuit is closed by means of the two-way key, *and the jockey is put at A*, no deflection in the galvanometer can be obtained by adjusting the rheostat. Thus the e m.f. of the standard cell is balanced across the resistance R (= 1018 ohms). Hence if E be the e. m. f of the standard cell, and i be the current flowing through R (or the potentiometer wire), we have

$$E = i R \qquad ...(1)$$

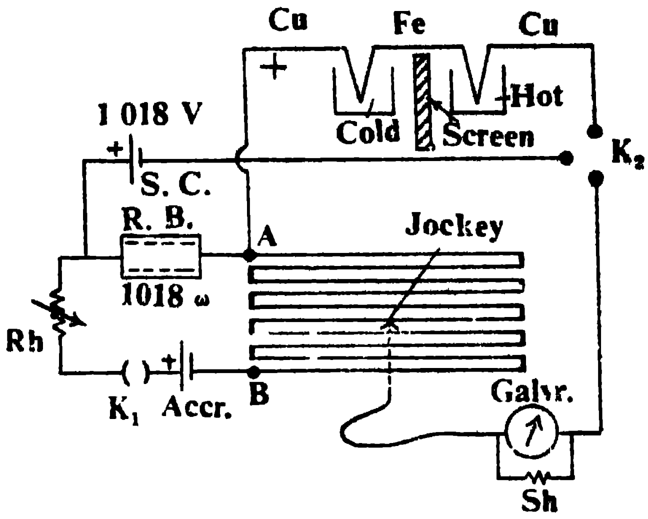

Fig. 76
Connection for a copper-iron thermocouple

Next let the standard cell circuit be broken, and the thermocouple circuit be connected to the galvanometer. Let the null-point be obtained at X, where AX = l. If e be the thermo-e m. f. and r be the resistance of the portion AX of the potentiometer wire, then

$$e = ir = i \rho l \qquad ... \qquad (2)$$

where ρ is the resistance per cm. of the wire*.

From (1) and (2) we have

$$e = \frac{\rho . E . l}{R} \qquad ... \qquad (3)$$

Equation (3) enables us to calculate the thermo-e. m. f. developed for this particular difference of temperature between the two junctions of the thermocouple.

Method

(i) Set up the electrical connections† as shown in fig.-76.

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* A preliminary experiment gives the value of ρ by determining the resistance of the ten wires of the potentiometer.

† In this arrangement the most important connection is that of the positive end of the thermocouple to the potentiometer wire. The copper wire connected to the *cold end of the thermocouple* should be connected to A (which is connected to the positive pole of the accumulator) Note that *in a copper-iron thermocouple junction is positive.*

If a *copper-constantan thermocouple* is employed for this experiment, then its *hot end* (which is positive in this case) should be connected to A (the higher potential terminal of the potentiometer wire).

The rheostat in the accumulator circuit should be of a high value, and for R insert a resistance box from which a resistance of 1018 ohms can be unplugged.

(ii) Shunt the galvanometer and put the jockey at A. Adjust the rheostat till there is practically no deflection in the galvanometer. Remove the shunt and obtain the exact position of the null point by finally adjusting the rheostat. Now, the e. m. f. of the standard cell has been balanced by the potential difference across R.

(iii) Re-shunt the galvanometer and bring the thermocouple in circuit with the help of the two-way key. When the temperature of the hot junction has become steady, press the jockey on a wire and by adjusting the length of the potentiometer wire obtain the approximate position of the null point. Get the exact position by removing the shunt from the galvanometer. Note the length of the potentiometer wire from A to that point where the null point has been obtained.

(iv) Re-check the standardisation of the potentiometer by bringing in the standard cell again in circuit and repeating the process as above. Finally, repeat the experiment twice or thrice and obtain a mean value of *l*. Calculate the thermo-e. m. f. with the help of the above formula, taking the value of ρ as given.

Observations

S. No.	High resistance (R)	Length of the potentiometer wire corresponding to thermo-e m.f.			Thermo-e. m. f. (e)	Remarks
		No. of complete wires	Length of the remaining wire	Total length (*l*)		
						(1) E.M.F. of the standard cell = ...volt (2) Resistance per unit length of the potentiometer wire = ...ohm.

Calculations.

$$e = \frac{\sigma E l}{R}$$

$$= \text{...microvolts*}$$

Result. The value of the thermo-e. m. f. for copper-iron thermocouple when its junctions are at ......°C and ......°C = ... microvolts.

[Standard value = ... μV ; Error = ...%]

Precautions and Sources of Error

(1) Before making connections the ends of the connecting wires should be carefully cleaned with a sand paper and then firmly secured between the binding terminals.

(2) The accumulator should be fully charged and should have a large capacity so that its e. m. f. may remain constant for the duration of the experiment.

(3) A plug key should invariably be employed in the accumulator circuit so that the current flows only when it is desired. This eliminates the unnecessary heating of the potentiometer wires, and secondly there is no unnecessary drain on the accumulator, which consequently helps to maintain a constant potential gradient along the potentiometer wires.

(4) When the standard cell is being balanced across the resistance R, the jockey of the potentiometer should lie at the end A of the potentiometer wire i. e., the standard cell is to be balanced across the resistance R only.

(5) The leads coming from the thermocouple should be sufficiently long so that their free ends are at the same temperature.

(6) The jockey should be pressed on the potentiometer wire momentarily. In no case should it be dragged along in the pressed position otherwise the wire will be rubbed off non-uniformly and its diameter will not be the same throughout.

(7) The galvanometer employed in this experiment should be a sensitive one. It should always be shunted in the initial stages of locating the null point. The shunt should be removed when the exact null-point is sought. The first operation ensures safety of the instrument while the second one utilises its full sensitivity without any fear of damage to it.

(8) The potentiometer should be so standardised that the potential gradient along the wire is of the order of a microvolt per division, which admits of sufficiently accurate measurements.

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* Convert the result is micro-volts. 1 mv = 10^{-6} volt.

For this purpose the high resistance R and the rheostat should each be about a thousand ohms.

ADDITIONAL EXPERIMENT

Exp.—35 (a)

Object. To study the variation of the thermo-electric e. m. f. with temperature for a copper-iron thermocouple and to determine its neutral temperature.

The experiment has to be conducted as the main experiment described above. As before the cold junction is placed in cold water contained in a beaker, and the hot junction is put in mercury contained in a hard glass (or pyrex) test tube which is heated in a sand bath. A thermometer reading upto, say, 350°C is put in this tube. The mercury is heated upto 320 C and then the readings of the thermo-e m. f. and the temperatures of the hot and cold ends are recorded after every 10°C fall of temperature.

[**Note.** It is essential to check the standardisation of the potentiometer after every four or five observations.]

Finally a graph is drawn between the thermo-e. m. f. (along the y-axis) and the difference in temperature (along the x-axis) between the hot and cold junctions. The graph will be a parabola from which the neutral temperature, which corresponds to the maximum e. m f., is noted.

[**Note.** The neutral temperature of a copper-iron thermocouple is 270°C (it may be different for different specimens of iron and copper). It may be added here that the neutral temperature for a thermocouple is a constant (i.e. it is independent of the temperature of the cold junction). The temperature of hot junction at which the thermo-e m.f. is zero and reversal takes place (i.e., the temperature of inversion) is a variable one, being always as much above the neutral temperature as the cold junction is below it.]

Expt.—35 (b)

Object. To determine the melting point of wax by measuring the thermo-e m. f.'s of a copper iron thermocouple.

After performing the above experiment put the hot junction in melting wax, and when the wax solidifies, measure the thermo-e.m.f. and corresponding to this value read the temperature from the graph. To this add the temperature of the cold bath. This is the melting point of wax.

[**Note.** The experiment can be performed by placing the hot junction in boiling water only, and noting the readings after every 5°C fall in temperature. The melting point can be calculated with the help of the graph.]

AMMETERS AND VOLTMETERS

Ammeters and voltmeters* are classed together because there is no essential difference in the principle involved in their operation. Except in the case of electrostatic instruments, a voltmeter carries a current which is proportional to the potential difference which is to be measured, and this current produces the operating torque. In an ammeter this torque is produced by the current to be measured, or by a definite fraction of it. Thus, the only real difference between the two instruments is in the magnitude of the current producing the operating torque.

An ammeter is usually of *low resistance,* so that its connection in series with the circuit in which the current is to be measured does not appreciably alter the value of this current. A voltmeter, on the other hand, is connected in parallel with the potential difference to be measured, and must therefore have a *high resistance* so that the current drawn by it is small. As a matter of fact, a low range ammeter (i. e., one which gives full scale deflection for a very small current) may be used as a voltmeter if a high resistance is connected in series with it. The current which flows through it when it, together with its series resistance, is connected across the voltage to be measured, must be within its range when used as an ammeter.

[Example

A milliammeter, whose resistance is 1 ohm, gives a full-scale deflection for a current of 10 milliamperes. Calculate the resistance which must be connected in series with it in order that it may be used as a voltmeter for reading voltages upto 10 volts.

Let x be the required resistance. The current flowing through the instrument when 10 volts are applied to the instrument and with this resistance in series, must be 10 milliamperes (or 0 01 amp.)

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* For a detailed study of galvanometers, ammeters and voltmeters, read author's book "A Critical Study of Practical Physics and Viva-Voce".

Thus

$$0{\cdot}01 = \frac{10}{x+1}$$

or
$$x + 1 = \frac{10}{0{\cdot}01} = 1000 \text{ ohms.}$$

$$\therefore \quad x = 999 \text{ ohms.]}$$

The relative magnitudes of the resistance of the two types of instruments is also warranted by consideration of power loss occurring in them. For instance, if R_A is the resistance of an ammeter in which a current I is flowing, the power loss in the instrument is I^2R_A watts. Again, if R_V is the resistance of a voltmeter to which a voltage E is applied, the power loss in the instrument is E^2/R_V. Obviously, in order that the power loss in the instruments shall be small, R_A must be small and R_V should be large.

Voltmeter. As indicated above, a voltmeter is always connected in parallel with the two points whose potential difference is to be measured. The internal resistance of the instrument should therefore be large in order to avoid any appreciable rearrangement of current and potential drop in the circuit The current passing through the voltmeter is consequently very small for such a high internal resistance, and hence the heating in the coil is small.

The internal resistance of the voltmeter is made up of not only that of the copper coil, but greater part is due to a high resistance put in series with it. The chief reason for this is to avoid any error due to the heating in the moving coil. Such heating can take place either due to (1) variations in the room temperature, or (2) the Joule heating. Due to both these causes the resistance of the coil shall increase. unless the temperature coefficient of its material is small. Apparently manganin, due to its low temperature coefficient is preferable but it has a serious drawback. For the same coil resistance a manganin coil shall have less radiating surface. Again, the effect of Joule heating can be eliminated by making the resistance of the moving coil fairly low. Hence a compromise between the two requirements is necessary. This is effected by taking a coil wound with copper coil which has a comparatively low resistance. In series with this is put a high resistance wire of a material, usually manganin, whose temperature coefficient is small, so that although the resistance of the coil may change considerably, the change in total resistance is small. This series resistance can be constructed of a thicker wire than would be possible for the moving coil.

In an actual instrument often used in the laboratary, the copper coil is wound on a metallic frame, so that when the coil moves in the magnetic field of the horse-shoe magnet, it cuts lines of force, thereby generating eddy currents in the frame, which oppose the motion of the coil bringing it quickly to rest and thus making the instrument a "dead-beat" one.

In such a moving coil instrument the direction of deflection depends on, the direction of the current. Hence, during insertion in the circuit, it should be carefully borne in mind that the positively marked terminal is connected to that point which has a higher potential, otherwise the needle may be damaged.

[**Note**. Sometimes the same voltmeter may be used to measure potential difference of different ranges. Thus if A and B terminals are connected to a difference of potential of 5 volts a full scale deflection is obtained in the instrument. If the resistance of the coil and the part L N of the resistance wire be 300 ohms, the current flowing in the coil will be 5/300 = 1/60 amp.

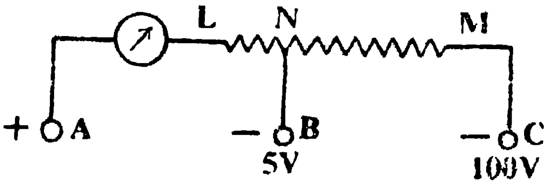

Fig. 77
A multiple-range voltmeter

If the same scale is to be employed to read 100 volts, the terminals A and C may be employed, so that an additional resistance NM is included in the circuit. Since the current is the same as before, we have

$$\frac{1}{60} = \frac{100}{R} \qquad \text{or} \qquad R = 6000 \text{ ohms}$$

where R is the total resistance (coil + external wire) of the circuit. Thus, to read 5 volts and 100 volts the scale will be divided in equal intervals, and each division will correspond to twenty times the value which corresponds to the lower range applied between AB.

If an instrument is intended to read millivolts, its internal resistance should be smaller, as can be easily worked out by pushing the above argument further.]

Ammeter. The resistance of an ammeter is small. This condition is achieved by connecting a low resistance in parallel with the moving coil. This resistance is referred to as a *shunt*, and in a fixed range ammeter it is contained inside the case. The value of the shunt resistance is small, hence the resistance of the whole instrument is also of the same order. The shunts are made of manganin since this material has a low temperature coefficient The dimensions of a particular manganin strip required to have a particular range ammeter are easily calculated out. If, in a particular case it is revealed that the shunt should have excessive width so that heating produced may be negligible, in that case not one, but several strips, are used in parallel.

It is easy to see that the shunt resistance is controlled by the ammeter range. The greater the range, the smaller is the resistance of the shunt. In fact, superior types of ammeters are not provided with fixed shunts, but are provided with external ones, thus the range can be suitably varied by using a shunt of appropriate value. The instrument is made dead-beat, like the voltmeter by winding the coil on a metallic frame in which eddy currents are produced, and they bring about the required damping. The ammeter, like the voltmeter, is a uni-directional instrument, hence it has to be inserted in a circuit in such a way that its positively marked terminal is connected to the higher potential point of the circuit.

From a brief resume of these two important instruments it is clearly seen that they are essentially moving coil galvanometers with slight variations in their construction, which is necessitated by the particular role which they have to perform in electrical measurements. Below are described and discussed two experiments which bring out how a galvanometer can be adopted either for direct current measurements or for direct voltage measurements.

EXPERIMENT—36

Object. To convert a given Weston galvanometer into an ammeter of a given range.

Apparatus Required*. Weston galvanometer† a high resistance box (preferably of dial pattern), an accumulator, a high resistance voltmeter, plug-key, an ammeter of the same range as given for conversion.

Formula Employed. The shunt resistance, S, required for converting the galvanometer into an ammeter of a given range is calculated with the help of the formula—

$$S = \frac{I_g}{I - I_g} \cdot G$$

where G = Galvanometer resistance

I_g = Value of the current required to get a full-scale deflection in the galvanometer

I = Value of the current which has to be read by the galvanometer (i.e., its range)

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* In this experiment the resistance of the galvanometer has to be known. If its value is not given, it has to be determined by Kelvin's method. In that case necessary apparatus for conducting this part of the experiment is also required [see expt.-13].

† For this experiment it is preferable to use a special type of galvanometer, the zero of whose scale lies on the extreme left as in the case of ammeter and voltmeter scales.

The length of the shunt wire can be calculated with the help of the formula—

$$S = l\rho$$

where l = Length of the shunt wire

ρ = Resistance *per unit length* of the shunt wire.

PRINCIPLE AND THEORY OF THE EXPERIMENT

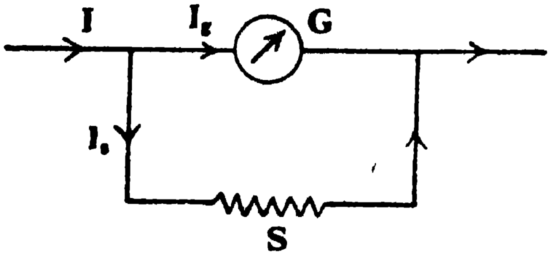

Fig. 78
Principle of an ammeter

The accompanying diagram represents a galvanometer of resistance G, in parallel with which a shunt of resistance S has been used. The main current I divides itself as shown in the figure. The currents obviously divided themselves in the inverse ratio of their resistances, that is,

$$\frac{I_s}{I_g} = \frac{G}{S}$$

or $$\frac{I_s + I_g}{I_g} = \frac{G + S}{S} \qquad \text{[By adding 1 to both sides]}$$

or $$\frac{I}{I_g} = \frac{G + S}{S} \qquad [\because I_s + I_g = I]$$

Thus the current I_g flowing through the galvanometer is a fraction of the main current and is equal to $\frac{S}{S + G}$. The value of S can be so adjusted that the fraction of the main current which the instrument is required to measure, is just sufficient to deflect the galvanometer needle through the whole range of the scale. The shunt resistance, from the above equation, is given by

$$S = \frac{I_g}{I - I_g} . G \qquad \ldots \qquad (1)$$

It is clear from this formula that if I_g is the current required by the galvanometer coil to produce a full range deflection of the needle, and if we wish to measure a higher current I with its help, we have to insert a shunt resistance S across the galvanometer coil, so that only I_g flows through the coil (thereby still producing the full range deflection), the remaining current being carried through the shunt.

Thus, to evaluate S to give a particular range (I) to the galvanometer, we have to determine the *figure of merit* of the

galvanometer, i. e., we have to know how much current should be sent through the galvanometer in order to produce a deflection of one division on the scale. Thus, if k be the figure of merit of the galvanometer, and n be the number of divisions on the scale, then

$$I_g = k. n. \qquad \dots \qquad (2)$$

[Note. The following numerical example shall make the whole reasoning of the process very clear—

A galvanometer of resistance 30 ohms is provided with a pointer and a scale having 100 divisions. When a current of 2×10^{-4} amperes flows through the galvanometer, the needle is deflected through 1 division on the scale. What should be the resistance of the shunt so that the galvanometer may read 5 amps ?

From this problem it is clear that the figure of merit of the galvanometer is 2×10^{-4} amp. per division. Thus to produce a full scale deflection a current of $2 \times 10^{-4} \times 100 = 0{\cdot}02$ amp. is needed to pass through the galvanometer. If we wish to measure 5 amps. with it, we should use a shunt of resistance S such that 0·02 amp. current flows through the galvanometer, and the remaining current, (5—0·02) =4·98 amp., passes through the shunt. Thus

$$\frac{S}{30} = \frac{0{\cdot}02}{4{\cdot}98} \qquad \therefore\ S = 0{\cdot}121 \text{ ohm}].$$

Method

[A] *Determination of the galvanometer resistance.*

[Note. If the galvanometer resistance is not given, determine it with the help of Kelvin's method, as described in expt.—13

[B] *Determination of the figure of merit of the galvanometer.*

For this set up the apparatus as shown in fig.-79. E is an accumulator connected in series with the galvanometer through a resistance box (preferably of the dial type) capable of giving high values for the resistance.

Adjust a high resistance of about 5000 ohms in the box and close the key. A deflection will be produced in G. Now adjust the resistance in the box till a readable deflection is produced in the galvanometer. Note the resistance R and count the number of divisions of deflection. Measure the E. M. F., (E), of the cell *with a high resistance voltmeter*. Then

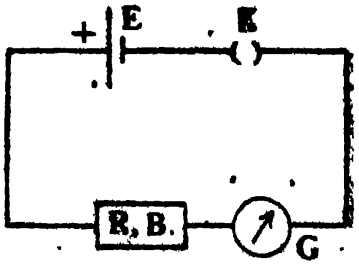

Fig. 79
Figure of merit of a galvanometer

$$k = \frac{I}{n_1} = \frac{E}{n_1 (R + G)}$$

where n_1 is the number of divisions through which the needle has been deflected when a current (say, I) flows through the circuit. If the total number of divisions on the galvanometer scale be n, then $I_g = kn$, which can be calculated out.

[C] *Determination of the shunt resistance and length of the shunt wire.*

Calculate the shunt resistance S from the equation (i) given above.

Now take a manganin wire and determine carefully the resistance for exactly one metre length of it with the post office box in the usual way. From this calculate ρ, the resistance per unit length of the wire. Then S/ρ will give the required length of the shunt wire. Cut a piece slightly longer than this calculated length and mark two points equidistant from the ends so that the length in between the marks is the calculated length. Connect the wire across the terminals of the galvanometer so that the marked points are just outside its binding terminals.

Now the galvanometer in conjunction with this length of shunt wire (of this thickness) has been converted into an ammeter which can read currents upto I amps.

[D] *Calibration of the converted galvanometer.*

Now set up an electrical circuit as shown in fig -80, in which A is an ammeter of nearly the same range as the converted galvanometer. Introduce a high resistance in the box and after pressing the key K take the reading of G and A. Convert the galvanometer reading to amperes and find the difference, if any, between the readings of the two instruments. This gives the error* of the galvanometer reading. In this way calibrate the whole dial of G and plot a graph taking the galvanometer readings as abscissae and corresponding ammeter readings as ordinates. This graph will be nearly a straight line and it will represent the calibration curve of the shunted galvanometer.

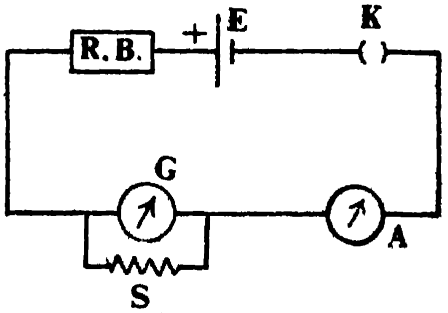

Fig. 80
Calibration of a galvanometer converted into an ammeter

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* For more accurate work calibrate the shunted galvanometer with a potentiometer.

Observations

[A *Readings for the determination of the resistance of the galvanometer.*

[Note. See expt —13]

[B] *Readings for the figure of merit of the galvanometer.*

S. No.	Resistance introduced in the R. Box (R)	Deflection in the galvanometer (n_1)	Figure of Merit of the galvanometer (k)	Remarks
				1. No. of divisions on the galvanometer scale (n) = ... 2. E. M. F. of the cell (E) = ... volts.
		Mean		

[C] *Readings for resistance per unit length of the shunt wire.*

[Note—Make a table similar to one required for the resistance of the galvanometer.]

[D] *Calibration of the shunted galvanometer.*

S. No.	Reading of the shunted galvanometer		Ammeter reading (I′)	Error (I + I′)
	in divs.	in amps. (I)		

Calculations

(i) Current (I_g) required to produce a full scale deflection in the galvanometer $= k \times n = \ldots$amp.

Now, (ii) Shunt resistance (S) $\dfrac{I_g . G}{I - I_g}$ ... ohms.

Again, (iii) Resistance of the shunt wire per unit length, i. e., $\rho = \ldots$ ohm/cm.

(iv) Length of the shunt wire required $= S/\rho = \ldots$ cms.

Result. The length of the shunt wire of S. W. G. ...required to convert the given galvanometer into an ammeter of range ... amp. = ... cms.

Precautions and Sources of Error

[Note—For the precautions connected with the relevant experiments, see them at the places referred to above.]

(1) The accumulator used in this experiment should be fully charged and should be of a fairly large capacity, so that it gives a constant current.

(2) The resistance box should be a high resistance one and should preferably be of a dial pattern. *At no stage of the experiment should the resistance in the box be zero or small*, otherwise an excessive current shall flow through the galvanometer or ammeter which will consequently be damaged.

(3) The zero reading, if any, in the instruments should be carefully noted down and accounted for in the calculations. The ammeter used in the calibration part of the experiment should preferably be of the same range as the one which has been prepared with the shunted galvanometer.

(4) In this experiment the galvanometer is a uni-directional one, hence its positively marked terminal should be connected to the higher potential point of the circuit.

(5) While connecting the shunt wire across the galvanometer care should be taken to see that exactly the measured length is in parallel with the instrument.

EXPERIMENT—37

Object. To convert a Weston galvanometer into a voltmeter of a given range.

Apparatus Required*. Weston galvanometer†, a high resistance dial pattern resistance box, an accumulator, plug key, a high resistance voltmeter (to read the E M. F. of the cell), another voltmeter preferably of the same range as the one given for conversion.

* In this experiment the resistance of the galvanometer has to be known. If its value is not given (which should normally be given), in that case it has to be determined by Kelvin's method. In that case the necessary apparatus shall also be required. (See expt.—13).

† For this experiment it is preferable to use a special type of galvanometer, the zero mark of whose scale lies on the extreme left (and not in the centre as is usually the case) as in the case of ammeter and voltmeter scale.

Formula Employed—The series resistance R needed to convert the galvanometer into a voltmeter of a given range is calculated with the help of the formula—

$$R = \frac{V}{I_g} - G$$

where G = Galvanometer resistance.

V = P. D. that has to be read with the converted galvanometer (*e. g.*, the required range).

I_g = Value of the current required to get a full-scale deflection in the galvanometer.

PRINCIPLE AND THEORY OF THE EXPERIMENT

In the accompanying figure G is a galvanometer which requires a current, say, I_g to produce a full-scale deflection of its pointer. Now we have to read a potential difference of V volts with the help of this galvanometer. It is easy to understand that if we connect the galvanometer directly with V, excessive current shall flow and the coil of the galvanometer shall be burnt out. No current greater than I_g should be allowed to flow through G. Obviously the excessive current can be cut down by inserting a resistance of proper value so that the requisite current I_g flows through the galvanometer. If this resistance be R, we have from Ohm's law—

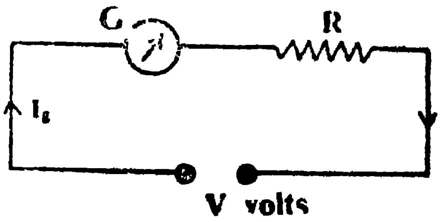

Fig. 81
Principle of a voltmeter

$$I_g = \frac{V}{G + R}$$

whence
$$R = \frac{V}{I_g} - G \quad \ldots \quad (1)$$

Thus to evaluate the series resistance we have to know the value of I_g. For this purpose we should determine the *figure of merit* of the given galvanometer, *i. e.*, we should know how much current should be sent through the galvanometer in order that a deflection of one division is produced on the graduated scale. Thus, if k be the figure of merit of the galvanometer, and n be the number of divisions on the scale then

$$I_g = kn \quad \ldots \quad (2)$$

[**Example**—In the numerical problem given in the body of the previous experiment let us calculate the series resistance which shall convert the galvanometer into a voltmeter reading upto 5 volts.

Now, the current required to produce a full-scale deflection of the galvanometer = 0·02 ampere

If a P. D. of 5 volts is directly applied to the terminals of the galvanometer, the current flowing through it will be equal to 5/30 = .0 17 ampere nearly, which is more than eight times the normal current, hence the galvanometer coil shall be burnt out.

Hence to reduce this current to the normal value of 0·02 amp. and at the same time to convert the galvanometer into a voltmeter, a series resistance should be added. The resistance of this wire shall be given by

$$R = \frac{V}{I_g} - G = \frac{5}{0 \cdot 02} - 30 = 220 \text{ ohms.} \,]$$

Method

[A] *Determination of the galvanometer resistance.*

[**Note**—If the galvanometer resistance is not given, determine it by Kelvin's method. See expt.—13]

[B] *Determination of the figure of merit of the galvanometer.*

[**Note**—This has been fully discussed in the previous experiment]

[C] *Determination of the series resistance and the length of the wire*—From the above determinations calculate the value of R, the series resistance, with the help of equation (1) given above. Now take a manganin wire and determine the resistance* of *exactly* 1 metre length of the wire with a post-office box in the usual way.

From this calculate ρ the resistance per unit length (*i. e.* per cm.) of the wire. Hence the length of the wire required to be connected with the galvanometer $= R/\rho$. Connect this length in series with the galvanometer. Now the given galvanometer in conjunction with this length of resistance (of this thickness) has been converted into a voltmeter and can read voltages upto V volts.

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* Alternatively, knowing the gauge number of the wire the resistance per metre can be obtained from the Tables of Constants.

[D] *Calibration of the converted galvanometer*—Set up the apparatus as shown in fig.-82, in which Rh is a rheostat, whose fixed terminals are connected to E. V is a voltmeter of nearly the same range as that of the converted galvanometer.

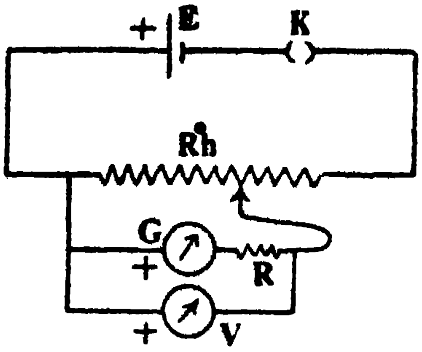

Fig. 82
Calibration of a galvanometer converted into a voltmeter

By shifting the position of the sliding contact of the rheostat, take a number of readings in G and their corresponding ones in V. Convert the galvanometer readings into volts and calculate the error†, if any, between the two values. In this way calibrate the whole dial of G and plot a graph between the galvanometer readings (represented on the x-axis) and the corresponding voltmeter readings (represented on the y-axis). This is the calibration curve of the galvanometer converted into a voltmeter.

Observations

[Note. Make appropriate tables with the help of those given in the previous experiment.]

Calculations

(i) Current (I_g) required to produce full scale deflection of the galvanometer $=$ kn $=$..... amp.

(ii) Series resistance (R) $= V/I_g - G =$ ... ohm

(iii) Resistance of this wire per unit length, $\rho =$...ohm/cm

(iv) Length of the wire required to be put in series with the galvanometer $= R/\rho =$ ... cm

Result. The length of the manganin wire of S. W. G. ...... required to convert the given galvanometer into a voltmeter of range.........volts =.........cms.

Precautions and Sources of Error

[Note. For precautions connected with relevant experiments other than this, see them at their appropriate places referred to in the body of the text.]

(1) The accumulator used in this experiment should be fully charged and should be of a fairly large capacity, so that it gives a constant current throughout the experiment.

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† For more accurate work the converted galvanometer should be calibrated with a potentiometer.

(2) The resistance box should be a high resistance one, and should preferably be of a dial pattern. *At no stage of the experiment should the resistance in the box be zero or small*, otherwise an excessive current shall flow through the galvanometer which will consequently be damaged.

(3) The zero reading if any in the galvanometer or the voltmeter should be carefully noted down and accounted for in the calculations. The voltmeter used in the calibration part of the experiment should preferably be of the same range as the one which has been prepared with the galvanometer.

(4) In this experiment the galvanometer used is a unidirectional one, hence its positively marked terminal should be connected to the higher potential point in the circuit. The same precaution should be observed with the voltmeter.

(5) While connecting the wire in series with the galvanometer it should be carefully noted that *only the marked length*, as required by calculation, is in series with the circuit, the extra portions of the wire on either end should be inside the appropriate binding terminals.

MISCELLANEOUS EXPERIMENTS

EXPERIMENT—38

Object. To determine the frequency of A. C. mains with the help of an electrical vibrator.

Apparatus Required. Electrical vibrator, a friction-less pulley, a uniform cord, a small pan, and a weight box.

Description of the Apparatus*. The *Electrical Vibrator* consists

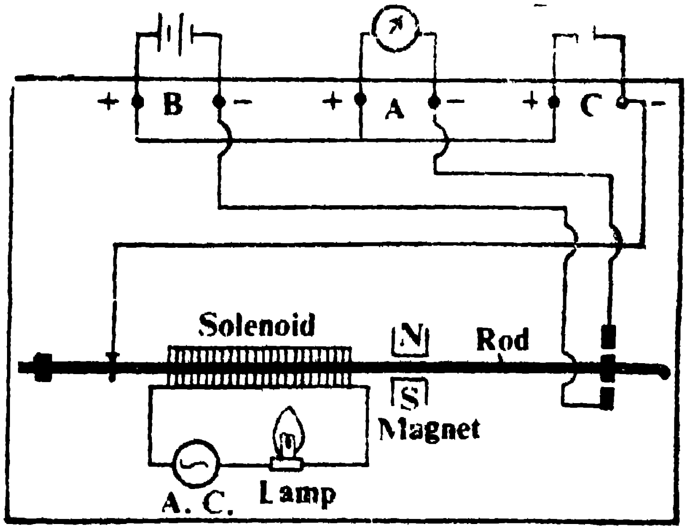

Fig. 83
An electric vibrator

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* Since this vibrator can also be employed *for the determination of the capacity of a condenser,* terminals marked B (for connecting a Battery), A (for a micro-Ammeter), C (for a Condenser) are also provided on its baseboard. Internal connections are provided as shown in the figure. The steel rod carries near its hooked end a small iron piece with flat ends. When the rod is set vibrating, it makes, with the help of this iron piece, alternate contact with the terminals provided nearby. This operation during one half cycle of the alternating current charges the condenser, while during the other half cycle the condenser is discharged through the microammeter. For, performing this experiment there is no need of using the thread.

of a solenoid through which passes a steel rod one end of which can be clamped, the other end ends in a hook to which a string under tension can be attached. The solenoid is energised by current drawn from the A. C. mains through a suitable bulb resistance. The steel rod passes through the pole-pieces of a permanent horse-shoe magnet mounted on the baseboard.

Formula Employed. The frequency (n) of the A. C. mains is given by the formula—

$$n = \frac{1}{2l}\sqrt{\frac{T}{m}} = \frac{1}{2l}\sqrt{\frac{Mg}{m}}$$

where T = Tension applied to the string

= Mg (M = mass hung at the end of the string)

m = Mass per unit length of the string

l = Length of one loop of the vibrating string

PRINCIPLE AND THEORY OF THE EXPERIMENT

When the solenoid is energised by passing an alternating current through it, the steel rod placed inside it gets magnetised longitudinally with its polarity reversing during each half cycle of the current. The magnetic field supplied by the permanent horse-shoe magnet produces oscillations by interacting with the magnetised rod, the necessary energy being derived from the electric supply. The length of the steel rod can be adjusted so as to get resonant vibration indicated by a large amplitude of vibration of its free end. The vibrations are communicated to the stretched string which begins to vibrate in a number of segments*, the frequency of the string being the same as of the rod, which is vibrating with the frequency of the A. C. mains If l be the length of one loop of the string, the frequency of the string is given by—

$$n = \frac{\nu}{\lambda} = \frac{\nu}{2l} = \frac{1}{2l}\sqrt{\frac{T}{m}} \quad \left(\because \nu = \sqrt{T/m} \right)$$

where T is the tension and m is the mass per unit length of the string. This is also the frequency of the A. C. mains.

Method

(i) After inserting a 25-watt lamp in the socket provided for it on the baseboard, switch on the current and adjust the length of the steel rod so that it is thrown in resonant vibration as evidenced by the amplitude attained by the free end.

---

* Stationary waves are produced in the string forming nodes and antinodes. Thus the string is divided in several segments. If the length of one segment be l, we have $l = \lambda/2$, where λ is the wavelength of the waves travelling along the string.

(ii) Now switch off the current and tie a uniform cord to the road. Pass the cord over a frictionless pulley attached to the table, and to its free end tie a light pan. Put some weight on the pan.

(iii) Switch on the current when the string will be found to vibrate in a number of loops, which can be sharply defined by displacing the vibrator thereby altering the length of the cord. Mark the position of the nodes and measure the distance between the consecutive nodes, and thus determine mean length* of a loop.

(iv) Repeat this process by keeping the tension constant and altering the length of the cord vibrating in resonance with the rod. Calculate the mean value of the length (*l*) of one loop.

(v) Weigh the pan and compute the total tension applied to the cord Also weigh an *exactly* measured length (say, 2 metres) of the cord in a chemical balance, and thereby calculate **m**, the mass per unit length of the cord

Calculate the frequency† from the formula given above.

Observations

S. No.	No of loops	Length of the loops	Length of one loop (*l*)	Mass of the pan (m_1)	Mass placed on the pan (m_2)	Total mass hung M (m_1+m_2)	Remarks
1.							Mass of 200 cms of cord =...gm ∴ m =...gm/cm
2.							
3.							
		Mean					

[Note. Make similar tables for other values of the tension.]

Calculations $n = \frac{1}{2l}\sqrt{\frac{T}{m}} = \frac{1}{2l}\sqrt{\frac{Mg}{m}}$

$=$ ....cycles/sec.

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* As the exact position of the first and the last node cannot be ascertained, they can be omitted in this measurement.

† The experiment may be repeated by altering tension, and thereby calculating the mean value of the frequency.

[**Note.** If a number of readings for T and l have been taken then the frequency can be calculated by finding T and l^2 *for each set separately* and then calculating the mean value of T/l^2 from these values and putting this value of T/l^2 in the formula

$$n^2 = \frac{1}{4m}\left(\frac{T}{l^2}\right),]$$

Result. The frequency of A.C. mains = ...cycles/sec.

Precautions and Sources of Error

(1) For this experiment a cord possessing a fairly constant mass per unit length should be employed. Hence a fishing cord, which fulfils this condition satisfactorily, should be preferred.

(2) Initially when the steel rod vibrates, its length should be adjusted so that it vibrates in resonance with the frequency of the A. C. mains This is accomplished when the free end vibrates with maximum amplitude.

(3) The length of the cord should be so adjusted that the nodes formed on it are well-defined. Due to uncertainty in the exact location of the first and the last nodes, they should not be taken into account while measuring the length of a loop.

(4) The pulley employed in this experiment should be a frictionless one, otherwise the tension acting on the string shall be different from the one actually applied. This will then constitute a source of error.

ADDITIONAL EXPERIMENT

Expt.—38 (a)

As indicated above, the electrical vibrator can also be employed to determine the capacity of a condenser. For this purpose connect a battery at B, a micrometer* at A, and the given condenser at C. A study of the internal connections of the vibrator shall reveal that during one half of the cycle the vibrating rod makes contact with the battery and the condenser, thus charging it to a voltage E. During the next half cycle the condenser plates are short-circuited through the microammeter and thus the condenser gets discharged through it. If n be the frequency of the A. C. mains, this process of charge and discharge of the condenser is repeated n times per second. Thus, the charge passing through the microammeter per second (i. e., the value of the current flowing

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* If a micrometer is not available in the laboratory, a sensitive galvanometer can be employed, but in that case the figure of merit of the galvanometer should be known. If it is not known, it should be determined as described in expt.-36.

through it) is equal to nCE coulombs. Thus if I be the current recorded by the microammeter, we have I = nCE, or

$$C = \frac{I}{nE} = \frac{\text{Current}}{\text{Frequency} \times \text{Voltage}}.$$

[Note. For instance, in a particular experiment the microammeter registered a constant current of 200 μA, when the e. m. f. of the cell was 2 volts. Then

$$C = \frac{I}{nE} = \frac{200 \times 10^{-6}}{50^{*} \times 2} = 2 \times 10^{-6} \text{ farads, or } = 2\mu\text{f.}]$$

For the success of the experiment it may be necessary to adjust the contact of the vibrating rod with the flat discs provided, so that the microammeter registers a steady deflection when the vibrator is working. Moreover, the e. m. f. of the cell should be recorded with the help of a high resistance voltmeter.

EXPERIMENT—39

Object. To determine the frequency of A. C. mains by means of a sonometer.

Apparatus Required. A vertical pattern sonometer, a solenoid with a soft iron core, a pan (or a hanger), half kgm-weights, chemical balance and weight box.

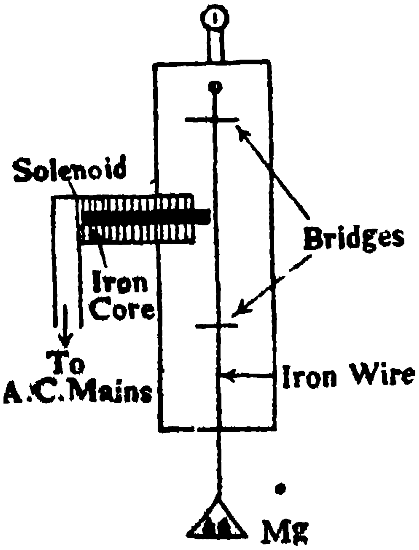

Fig. 84
Vertical sonometer for frequency of A. C. mains

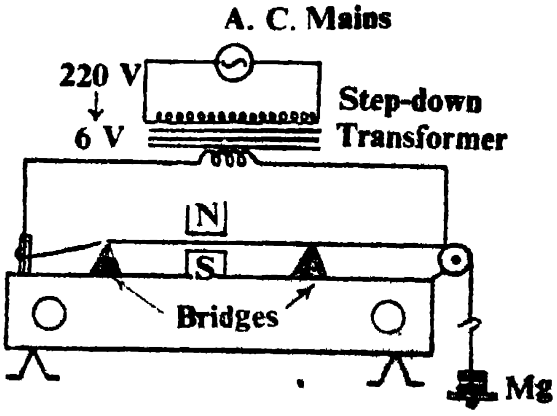

Fig. 85
Horizontal sonometer for frequency of A. C. mains

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* The frequency available for the city supply is generally 50 cycles/sec.

Description of the Apparatus. The apparatus consists of a vertical pattern sonometer on which is stretched an *iron* wire. A solenoid having a large number of turns of insulated copper wire and carrying a soft iron core along its axis is clamped near the middle of the segment of the wire between the two bridges. The lower end of the wire carries a pan on which suitable weights can be placed.

[**Note.** Another variation of the apparatus* is the usual horizontal pattern sonometer on which is stretched a *brass* wire. The alternating voltage is stepped down to, say, 6 volts by means of a step-down transformer and then is connected to the wire as shown. The wire passes between the pole-pieces N and S of a permanent horse shoe magnet. The wire therefore experiences an alternating force due to the field of the magnet on the current in the wire, and for a particular length of the wire between the bridges it is thrown into resonance as is evidenced by a large amplitude. This condition is achieved when the frequency of the alternating current passing through the wire is equal to its mechanical frequency of vibration, which is given by the formula $n = \frac{1}{2l}\sqrt{\frac{T}{m}}$]

Formula Employed†. The frequency (n) of the mains is given by the formula—

$$n = \frac{1}{4l}\sqrt{\frac{T}{m}}$$

where l = Length of the sonometer wire between the two bridges when it is thrown in resonant vibration.

T = Tension applied to the wire.

m = Mass per unit length of the wire.

PRINCIPLE AND THEORY OF THE EXPERIMENT

If an alternating current is passed through a solenoid having a soft iron core, the core is temporarily magnetised twice during each cycle of alternation—first with one polarity when the oscillation of the current is in one direction, and then with the opposite polarity when the current flows in the opposite direction. When the sonometer wire is held close to the core, it will be pulled twice during each cycle, and consequently if the frequency of the alternating current be n, the wire shall be pulled 2n times per second. If the length and tension of the wire be so adjusted that its natural frequency is also 2n, the wire will be thrown in resonant

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* The vertical pattern is preferable to the horizontal one, since friction at the pulley is completely eliminated.

† Carefully note the difference in the two formulae.

vibration and the amplitude of vibration of the wire will be maximum. If the tension applied to the wire be T and m be the mass per unit length of the wire, the frequency of vibration N of the wire is given by—

$$N = \frac{1}{2l}\sqrt{\frac{T}{m}}$$

where l is the resonant length of the wire.

The frequency (n) of the A. C. mains will be equal to N/2. Hence

$$n = \frac{1}{4l}\sqrt{\frac{T}{m}}$$

Method

(i) Before starting the actual experiment, have an idea of the breaking stress for the material of the wire from the Table of Physical Constants. From this value calculate the breaking tension (= breaking stress × area of cross-section of the wire) for your wire. During subsequent experiment the *weight in the pan should not exceed half the breaking tension.*

(ii) Suspend the sonometer from the nail on the wall and see that the pan provided below stays clear of the wall. Put a suitable load on the pan. Switch on the current and adjust the core of the solenoid near the middle of the wire between the bridges.

(iii) With the help of the bridges adjust the length of the wire till it begins to vibrate under the influence of the magnetic field provided by the core. During this adjustment the core should always be placed near about the middle of the vibrating wire.

Now by a slight delicate adjustment attain a position when the wire is thrown in violent resonant vibration and the amplitude is maximum.

(iv) Switch off the current and measure the length of the vibrating wire by holding a scale on the bridges and avoiding the error due to parallax. Record the tension, *which should include the mass of the pan or the hanger.*

(v) Change the tension in suitable steps and obtain the corresponding lengths of the vibrating wire. Now weigh in a chemical balance a known length (say, 100 cms) of the sonometer wire and thus calculate **m**, mass of the wire per unit length.

(vi) Calculate the frequency of the A. C. mains as indicated below.

Observations

S. No.	Tension* applied to the wire (T)	Length of the resonating wire (l)	l^2	Remarks
				Mass of 100 cms. of wire = ...gm. ∴ m = ...gm/cm.
Mean		Mean		

Calculations

Substituting the mean values of T and l^2 in the formula we have—

$$n^2 = \frac{1}{4m} \cdot \left(\frac{T}{l^2} \right)$$

$$= \dots \dots \dots$$

Hence $= \dots \dots$ cycles/sec.

Result. The frequency of the A. C. mains = ... cycles/sec.

Precautions and Sources of Error

(1) The sonometer wire should be uniform and free from kinks.

(2) For bringing the wire in resonant vibration, start with a small length of the wire and increase the length in small steps. The solenoid should be so placed that its iron core is situated close to the middle of the vibrating portion of the wire.

(3) While finding out the tension of the wire, do not forget to add the mass of the pan or of the hanger. If a sonometer employs a spring balance note down its zero error, if any.

(4) While increasing the tension of the wire, be careful that the wire is not stretched beyond the elastic limit. For this purpose, before starting the experiment have an idea of the magnitude of the breaking load of the given wire from the Table of Physical Constants.

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*This includes the mass of the pan (or the hanger).

(5) In the derivation of the formula $\nu = \sqrt{T/m}$ it has been assumed that the wire is perfectly flexible. Hence due to the rigidity of the experimental wire an error shall creep in the result.

(6) If the wire is not uniform or if its composition is variable then also the result will be erroneous.

(7) The tension on the two sides of the bridges may not be the same.

[Note If the horizontal pattern of the sonometer is employed, there will be an additional source of error. There may be friction at the pulley, hence the value of the tension is less than that actually applied. This consequently affects the value of the frequency.]

EXPERIMENT—40

Object. To determine the impedance of a given A. C. circuit.

Apparatus Required. An inductance, a condenser, a resistance, A. C. ammeter and voltmeter and flexible cord for making electrical connection.

Formula Employed. The impedance of the circuit is given by the following formula :—

$$Z = \frac{E_*}{I_*}$$

where Z = The required impedance

E_* = Virtual E. M. F. (as measured by A. C. voltmeter)

I_* = Virtual Current (as measured by A. C. ammeter)

PRINCIPLE AND THEORY OF THE EXPERIMENT

Let a harmonically varying voltage, $E_0 \sin \omega t$, be applied to a circuit containing an inductance L, a resistance R, and a capacitance C in series, as shown in fig.–86. The value of the current flowing in this circuit is obtained by solving the potential equation of the circuit. The potential equation of the circuit is

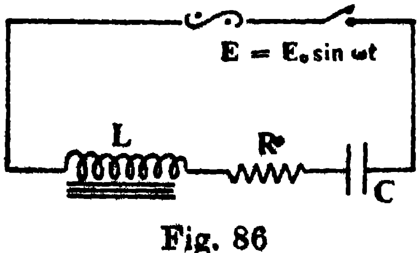

Fig. 86
Circuit containing L, C, and R

$$L\frac{dI}{dt} + IR + V = E_0 \sin \omega t \quad \dots (1)$$

where I is the instantaneous value of the current and V is the potential difference between the coatings of the condenser at that instant. If Q be the charge on the condenser at that moment, the above equation reduces to

$$L\frac{dI}{dt} + IR + \frac{Q}{C} = E_0 \sin \omega t \qquad \ldots \qquad (2)$$

Let the solution* of this equation be

$$I = I_0 \sin (\omega t - \phi) \qquad \ldots \qquad (3)$$

where I_0 and ϕ are to be determined. From (3) we have

$$\frac{dI}{dt} = I_0\, \omega \cos (\cos \omega t - \phi)$$

Now because $dQ = I \cdot dt = I_0 \sin (\omega t - \phi)\, dt$, we have on integrating this

$$Q = - \frac{I_0}{\omega} \cos (\omega t - \phi)$$

Substituting the values of these expressions in equation (2) we have

$$L\, I_0\, \omega \cos (\omega t - \phi) + I_0 R \sin (\omega t - \phi) - \frac{I_0}{C\,\omega} \cos (\omega t - \phi) = E_0 \sin \omega t$$

or
$$I_0 R \sin (\omega t - \phi) + I_0 \left(L\omega - \frac{1}{C\,\omega} \right) \cos (\omega t - \phi) = E_0 \sin \omega t$$

Comparing the coefficients of $\sin \omega t$ and $\cos \omega t$ on the two sides of this equation we have

$$I_0 R \cos \phi + I_0 (L\,\omega - 1\ C\,\omega) \sin \phi = E_0 \qquad \ldots \qquad (4)$$

and
$$-I_0 R \sin \phi + I_0 (L\,\omega - 1/C\,\omega) \cos \phi = 0 \qquad \ldots \qquad (5)$$

Now, squaring and adding (4) and (5) we have—

$$I_0^2 [R^2 + (L\,\omega - 1/C\,\omega)^2] = E_0^2$$

whence
$$I_0 = \frac{E_0}{\sqrt{R^2 + (L\,\omega - 1/C\,\omega)^2}} \qquad \ldots \qquad (6)$$

Also from equation (5) we have

$$\tan \phi = \frac{L\,\omega - 1/C\,\omega}{R} \qquad \ldots \qquad (7)$$

---

* The only part of the solution of equation (2) which is of importance to us is that in which the current has the same periodicity as the electromotive force, any other being quickly damped out.

Thus from equation (6) it is clear that effective resistance, or the impedance of the circuit is given by

$$Z = \sqrt{R^2 + (L\omega - 1/c\omega)^2} \quad \dots \quad (8)$$

where $L\omega$ is the inductive reactance and $1/c\omega$ is the capacitive reactance. From equation (6) we have

$$Z = \frac{E_0}{I_0} = \frac{E_0/\sqrt{2}}{I_0/\sqrt{2}} = \frac{E_*}{I_*} \quad \dots \quad (9)$$

where E_* and I_* are the virtual voltage and virtual current respectively. Normal A. C. measuring instruments† measure virtual values of voltage and current.

Thus by measuring E_* with an ordinary A. C. voltmeter and I_* with an A. C. ammeter, the impedance (Z) of the circuit can be evaluated.

Method

(i) Set up the apparatus as shown in fig.–87. Connect the primary of the step-down transformer to the A. C. mains. The secondary is connected through a rheostat to a choke coil (L), a condenser (C), and a resistance (R). Connect the A. C. ammeter (A) in series and the A. C. voltmeter (V) in parallel with this circuit.

(ii) When the connections have been properly made, switch on the current and for a particular setting of the rheostat record the readings of the ammeter and the voltmeter. In this way by adjusting the rheostat take several readings for the values of the current and the voltage.

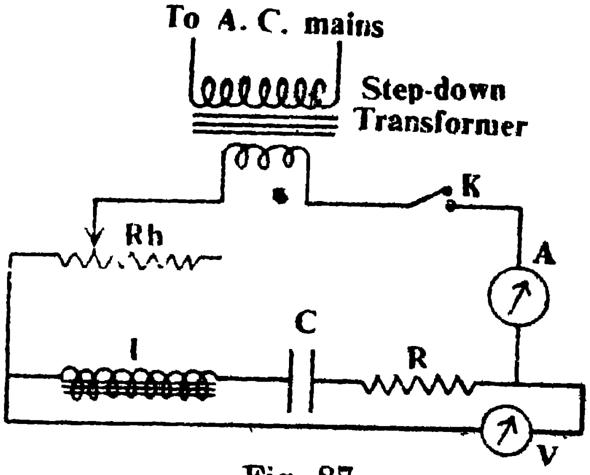

Fig. 87
Impedance of an A. C. circuit

(iii) Plot a graph between virtual volts V_* (represented along the y—axis) and virtual amperes I_* (represented along the

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† For a detailed study of these instruments read author's book "A Critical Study of Practical Physics and Viva-Voce."

x-axis). The graph shall be a straight line. The slope (= tan θ) of the straight line gives the impedance of the circuit.

(iv) Calculate also the value of the impedance by taking the known values of L, C, and R, and substituting these values in equation (8) given above.

Observations

S. N.	Voltmeter reading (V_*)	Ammeter reading (I_*)	Slope of the graph (Z)
1	...... volts	...... amps.	
⋮			...... ohms.
⋮			

Calculations

From the graph, $Z = \frac{V_*}{I_*} = \ldots$ ohms

Again $Z = \sqrt{R^2 + (L\omega - I/C\omega)^2}$

Here $R = \ldots$ ohms.

$L = \ldots$ henry

$C = \ldots$ farad

and $\omega = 2\pi n = 2\pi.\ 50$

Thus $Z = \ldots\ \ldots = \ldots$ ohms.

Result. The impedance of the given A. C. circuit ohms.

ADDITIONAL EXPERIMENTS

Expt.—40 (a)

Variation of impedance of the circuit with frequency and determination of L or C from the resonant frequency.

From the relation

$$I_* = \frac{E_*}{R^2 + L\omega - I/C\omega)^2}$$

it is clear that if the A. C. voltage be kept constant and its frequency be varied, the current amplitude changes. If we plot a graph between I on the y-axis and frequency (n) on the x-axis, we get a curve as shown in the accompanying figure. Obviously the maximum current amplitude is obtained when the impedance of the circuit is minimum. The impedance is minimum when

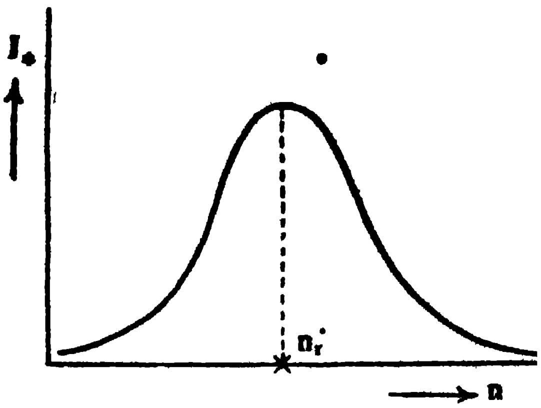


Fig. 88
Variation of current with frequency

$$L\omega - \frac{1}{C\omega} = 0 \text{ or } \omega^2 = \frac{1}{LC}$$

$$\text{Since } \omega = 2\pi n \text{ ; } n^2 = \frac{1}{4\pi LC}$$

$$\text{or} \qquad n = \frac{1}{2\pi\sqrt{LC}}$$

When the frequency of the applied source is equal to this frequency, the circuit is said to be in resonance, and under this condition the current amplitude is maximum and the current and voltage are in phase with each other since tan $\phi = 0$. Since the inductive reactance cancels the effect of the capacitive reactance, the current in this case is determined purely by the ohmic resistance.

Now, to conduct this experiment an alternating voltage source of variable frequency is needed. For this purpose, a valve oscillator can be employed as a variable frequency source. The electrical connections are made as above, and after adjusting the source for the lowest frequency which it can produce, the readings of the voltmeter and the ammeter are taken. The frequency (n) of the source is varied in steps and the corresponding values of the voltage (E) and the current (I) are recorded. The value of the impedance (Z = E/I) is calculated for each value of the frequency (n). Finally a graph is drawn between these two quantities (n and Z) and the frequency corresponding to minimum impedance is noted. Now, resonant frequency

$$n_r = \frac{1}{2\pi\sqrt{LC}}$$

Hence knowing n_r from the graph L or C can [illegible] calculated if the other quantity is given.

Expt.—40 (b)

Determination of the frequency of the alternating voltage.

For this purpose a variable condenser of known capacity replaces the one used in the main circuit above. If the variable capacity is changed, the current in the circuit as read by the ammeter also changes. Now the capacity is varied in steps and its values as well as the corresponding values of the current are noted down. These are depicted on a graph from which the value of capacity C_r giving the maximum current in the circuit is noted. The frequency of the voltage is calculated from the formula

$$n_r = \frac{1}{2\pi\sqrt{L C_r}}$$

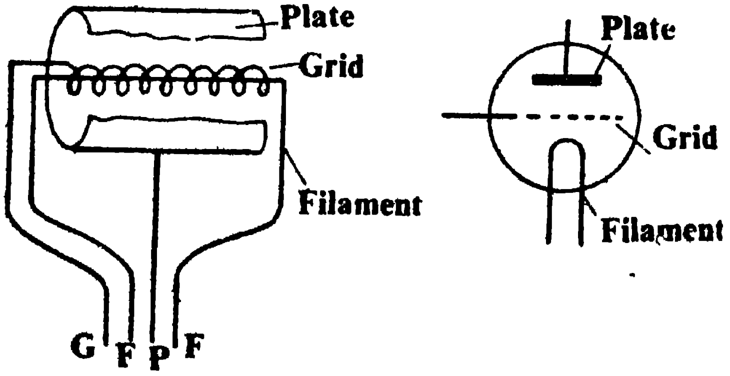
[**Note.** This method is more convenient if the frequency of the source is, say, of the order of 1000 cycles per sec. If the frequency to be measured is of the supply mains, which is generally 50 cycles per second, the method adopted in Expt.—38 or 39 is always preferred.]

EXPERIMENT—41

Object. To draw the characteristic curves between grid voltage and plate current of a triode valve and with the help of these curves to determine the values of the amplification factor, the plate resistance, and the mutual conductance of the valve.

Apparatus Required. A triode valve, characteristic-curve-apparatus fitted with meters, etc., a 2-volt accumulator, high tension battery, low tension battery, rheostats and plug-keys.

Description of the Triode Valve. When a metal is heated to a high temperature, it begins to emit electrons. This phenomenon, called the *therminoic emission*, is utilised in the construction of



(a) (b)

Fig. 89
A triode valve (sectional diagram)

valves. The triode or the three-electrode valve, invented by Lee de Forest in 1907, consists of three components—the filament, the grid, and the anode or the plate, all mounted in a glass or metallic tube which is either highly evacuated or contains a trace of an inert gas.

In one pattern of the triode valve (fig -89 a) the grid is an open spiral wire surrounding the filament, and the plate is a cylinder of thin metal enveloping the grid and the filament. Fig -89 (b) depicts the conventional mode of representing the valve in diagrams.

The filaments are generally of two types :—

(i) The *directly heated type*, in which the filament is either a pure tungsten wire, or a thoriated one, or coated with special active material, such as alkaline earth metals and their oxides.

(ii) The *indirectly heated type*, in which the filament consists of a metal tube with insulated heater wire of pure tungsten at the centre. The metallic tube is externally coated with electron-emitting oxides.

The grid is usually made of spiral or mesh of molybdenum wire wound in grooves in the supporting wire. The plate is usually a circular or flattened cylinder of nickel or iron.

When the filament is heated by passing an electric current through it the electrons emitted by it are attracted by the plate which is always maintained at a high positive potential with respect to the filament. The grid may be raised to a positive or negative potential with respect to the filament. Consequently the electrons coming from the filament will either be attracted or repelled by the grid. Thus the electronic current flowing from the filament is determined jointly by the potentials of the plate and the grid, but as the grid is situated closer to the filament than the plate, it is much more effective in controlling the plate current. Thus the grid acts as a control electrode in a triode valve.

Formula Employed*

(i) The *Amplification Factor* (μ) is determined by the formula—

$$\mu = \left|\frac{\Delta E_p}{\Delta E_g}\right|_{I_p} \quad \ldots \quad . \quad (1)$$

which means that if the plate voltage is increased by an amount ΔE_p, the grid voltage has to be decreased by ΔE_g in order to

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* The valve parameters are approximately constant over the straight part of the characteristic curves. (See fig.-92) hence their valves are determined only in this region.

keep the plate current I_p constant. As a matter of fact, amplification factor of a triode valve is a measure of the effectiveness of the grid with respect to the plate (or the anode) in controlling the plate (or anode) current, and may be defined as *the ratio of the change in the anode voltage, required to produce a certain change in the anode current, to the change in the grid voltage which would cause the same change in the anode current.*

(ii) The *Plate Resistance* (r_p) is calculated by the formula—

$$r_p = \left| \frac{\Delta E_p}{\Delta I_p} \right|_{E_g} \qquad \ldots \qquad (2)$$

which means that for a constant grid voltage E_g, a change in plate voltage by ΔE_p results in a corresponding change in plate current by ΔI_p. Plate resistance may be defined as the *reciprocal of the rate of variation of the anode current with anode voltage, when the grid voltage is kept constant.*

(iii) The *Mutual Conductance* (g_m) is evaluated from the formula—

$$g_m = \left| \frac{\Delta I_p}{\Delta E_p} \right|_{E_p} \qquad \ldots \qquad (3)$$

which means that for a fixed plate voltage E_p, if the grid voltage changes by ΔE_g, the corresponding change in the plate current is ΔI_p. *Mutual conductance may be defined as the rate of change of anode current with grid voltage, when the plate (or anode) voltage is kept constant.*

PRINCIPLE AND THEORY OF THE EXPERIMENT

When the filament (of a directly heated valve) or the separate heater-cathode (of an indirectly heated one) is electrically heated, it becomes a source of electrons which accumulate in the region surrounding the filament. If an external field is applied which removes the electrons as fast as they are produced, the electrons begin to drift in a continuous stream which constitutes an electric current. However, if the external field is not sufficiently great to remove the electrons as fast as they are produced, a cloud of electrons will perpetually be formed near the filament surface, and will consequently exert a repulsive force on those electrons which are just to leave the surface. This electron cloud is known as *Space Charge*. If the external field is withdrawn, the space charge may attain a value which repels all the electrons as soon as they are emitted. Under this circumstance the flow of the current will cease.

In a triode valve the external field round the filament is jointly applied by the grid and the plate. Voltages applied to the grid have a larger effect on the electrons emitted by the filament than the voltages applied to the plate since the grid is situated nearer the filament. The number of electrons drawn away from the filament is dependent on the plate voltage as well as the grid voltage, and since the grid does not obstruct the passage of electrons flowing through it, the electrons reach the plate constituting the plate current.

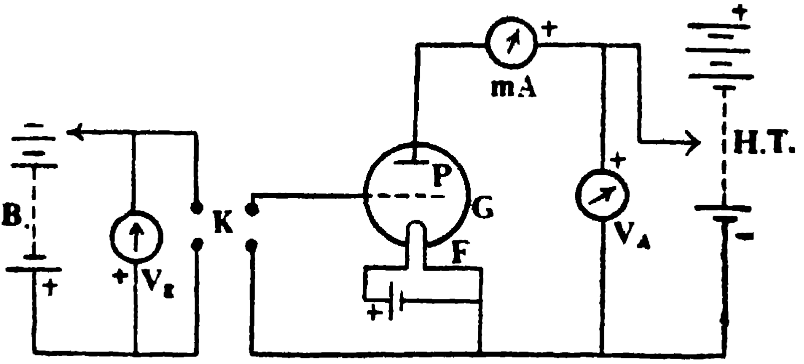

Fig. 90
Connections for a triode valve

Thus if the filament temperature is kept constant, the plate current I_p is a function of the plate voltage E_p as well as the grid voltage E_g. The most important characteristic curve* of a triode is the curve showing the variation of plate current with the variation of grid voltage for any fixed value of plate voltage. These curves can be studied with the help of the arrangement shown in fig.-90.

The filament F is heated by a 2-volt accumulator (or in accordance with the specifications prescribed by the maker for that particular valve), and the anode (plate) is connected to a high tension battery (H. T.) in series with a milliammeter (mA). The grid is connected to a variable grid-bias battery (G.B.) through a reversing key K. The characteristic curves obtained are of the type shown in the accompanying figure.

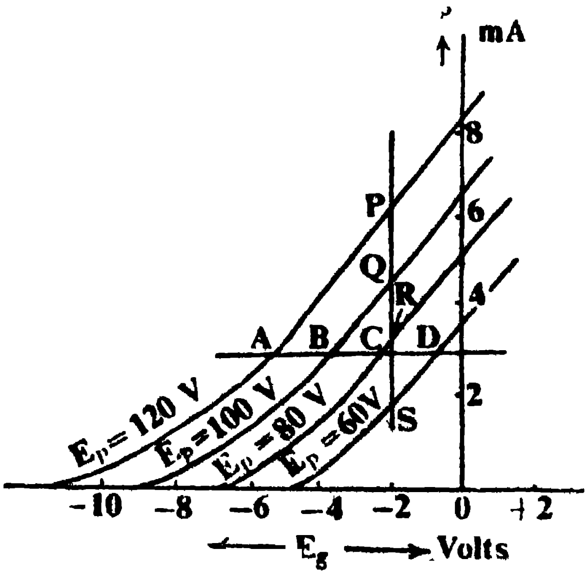

Fig. 91
Characteristic curves of triode

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* This is also known as a *mutual characteristic* to distinguish it from *anode characteristic* which depicts the variation of anode current with anode potential for any fixed grid voltage.

The tube parameters* are calculated as follows :—

(i) *Amplification Factor.* Draw a line parallel to the x-axis cutting the straight portions of the curves at A, B, C, and D respectively. As the plate current I_p has the same value at A, B, C, and D, the amplification factor is given by the following expression :—

$$\mu = \left|\frac{\Delta E_p}{\Delta E_g}\right|_{I_p} = \frac{V_A - V_B}{AB} = \frac{V_B - V_C}{BC} = \ldots \text{etc.}$$

The mean of these values may be taken as the amplification factor of the valve. Amplification factor has no unit and its value is always greater than unity.

(ii) *Plate Resistance*—Now draw a vertical line cutting the curves at P, Q, R, S respectively. Since E_g, the grid potential, is constant for all these points, the value of the plate resistance is given by—

$$r_p = \left|\frac{\Delta E_p}{\Delta I_p}\right|_{E_g} = \frac{V_P - V_Q}{PQ} = \frac{V_Q - V_R}{QR} = \ldots \text{ohms.}$$

The unit of plate resistance is "ohms".

(iii) *Mutual Conductance*—For this purpose consider any one curve, and select out two points such as B and Q. The plate voltage E_p remains constant, hence the mutual conductance.

$$gm = \left|\frac{\Delta I_p}{\Delta E_g}\right|_{E_p} = \frac{i_p}{e_g} \text{ mho}$$

where i_p is the difference in the plate current, and e_g is th difference in the grid voltage for these points. Values of mutua conductance are calculated on the four curves separately. Th unit of mutual conductance is "mho".

Metho:

(i) Before starting the actual experiment ascertain the specifications prescribed by the manufacturer for the particular valve under experimental study. These specifications should be

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* The experimentally determined values of these parameters can be employed to verify the relation—

$$\mu = r_p \times g_m$$

strictly followed. Now insert the valve in its socket and make the connections[*] as shown in fig.-90.

[Note—The high tension voltage may be had from a battery of dry cells, or it may be obtained from the D.C. mains, if available in the laboratory, with the help of resistances as shown in fig.-92. R is a fixed resistance which helps in creating a potential drop across the rheostat Rh, which is being used as a potential divider, from which suitable voltages can be tapped.

If an A.C. mains is available in the laboratory, the anode potentials can be taken by using a rectifier set, which may incorporate, for instance, a metal rectifier which changes the alternating current into a unidirectional pulsating current, which is further smoothened by a capacity and choke combination.]

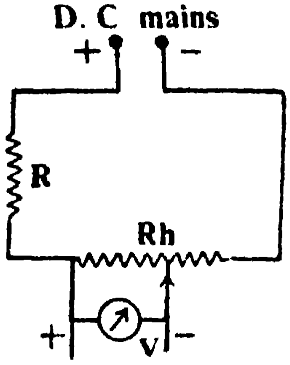

Fig. 92
High tension
for use with
a triode

(ii) Adjust the plate voltage to any convenient value (say, 60 volts), and connect the grid bias to the reversing key in such a way that the grid becomes negative with respect to the filament. Adjust the variable tap of the grid bias in such a way that the plate current is zero. Now change the grid bias in equal steps till the voltage applied to the grid is zero. Reverse the key now so that the grid becomes positive with respect to the filament. Increase the grid voltage in steps to the maximum *permissible value.* Record each value of the grid voltage and the corresponding anode current. Also note down the anode voltage[†].

(iii) Plot a curve between the grid voltage and the plate current taking the various grid voltage as abscissae and the corresponding values of the plate current as ordinates.

(iv) Now change the plate potential to, say, 80,100, volts etc. and take a few more sets of observations for the variation of the plate current with the grid potential, and draw similar curves[‡] on the same graph paper.

(v) Calculate the tube parameters as explained above.

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[*] If the apparatus supplied in the laboratory for this experiment is a ready-made one, then study the internal connections carefully, this is very essential.

[†] It is essential that throughout this measurement, the plate voltage, fixed earlier, is maintained constant.

[‡] A typical set of such curves obtained with a particular type of triode is illustrated on the graph at the end of this experiment.

Observations

S. No	Grid potential	Plate current when the plate potential is kept at a constant value of		
		60 volts	80 volts	100 volts
1.	... volt	... mA.	... mA.	... mA.

Calculations—From the graph

(i) *Amplification Factor,* $\mu = \frac{V_A - V_B}{AB} = \ldots = \ldots$

Similarly $\mu = \frac{V_B - V_C}{BC} = \ldots = \ldots$

... etc. ... etc. ...

$\therefore$ **Mean** $\mu = \ldots$.

(ii) *Plate Resistance,* $r_g = \frac{V_P - V_Q}{PQ} = \ldots = \ldots$ ohms

... etc. ... etc. ...

$\therefore$ **Mean** $r_p = \ldots$ **ohms**

(iii) *Mutual Conductance,* $g_m = \frac{i_p}{e_g}$

(a) For curve no. 1, $g_m \ldots = \ldots$ ohms

... etc. ... etc. ...

Result—The characteristic curves for the grid voltage and the plate current of the given triode valve are shown in fig.–93, and the values of the tube parameters are as follows :—

(i) Amplification factor = ...
(ii) Plate resistance = ... ohms
(iii) Mutual conductance = ... mhos

Precautions and Sources of Error

(1) The specifications prescribed by the manufacturer for the given triode should be strictly followed. If a specific value of the heating current for the filament has been prescribed, this should be adjusted to this value by including in this circuit a rheostat and an ammeter.

(2) The negative marked terminal of the milliammeter should be connected to the plate of the triode.

(3) While taking observations for the anode current with different grid voltages, the anode potential should be adjusted, if necessary, to its initial value. Moreover, it is well to arrange that the grid circuit is never broken while there is a high potential on the anode.

(4) The maximum voltage applied to the grid should not be more than 20 volts, otherwise the filament may be broken due to excessive mechanical strain.

(5) The characteristic curves should be drawn smooth on the graph paper and for the evaluation of the tube parameters the straight portions of the curves should be employed.

Note. [See the graph drawn in fig.-93.)

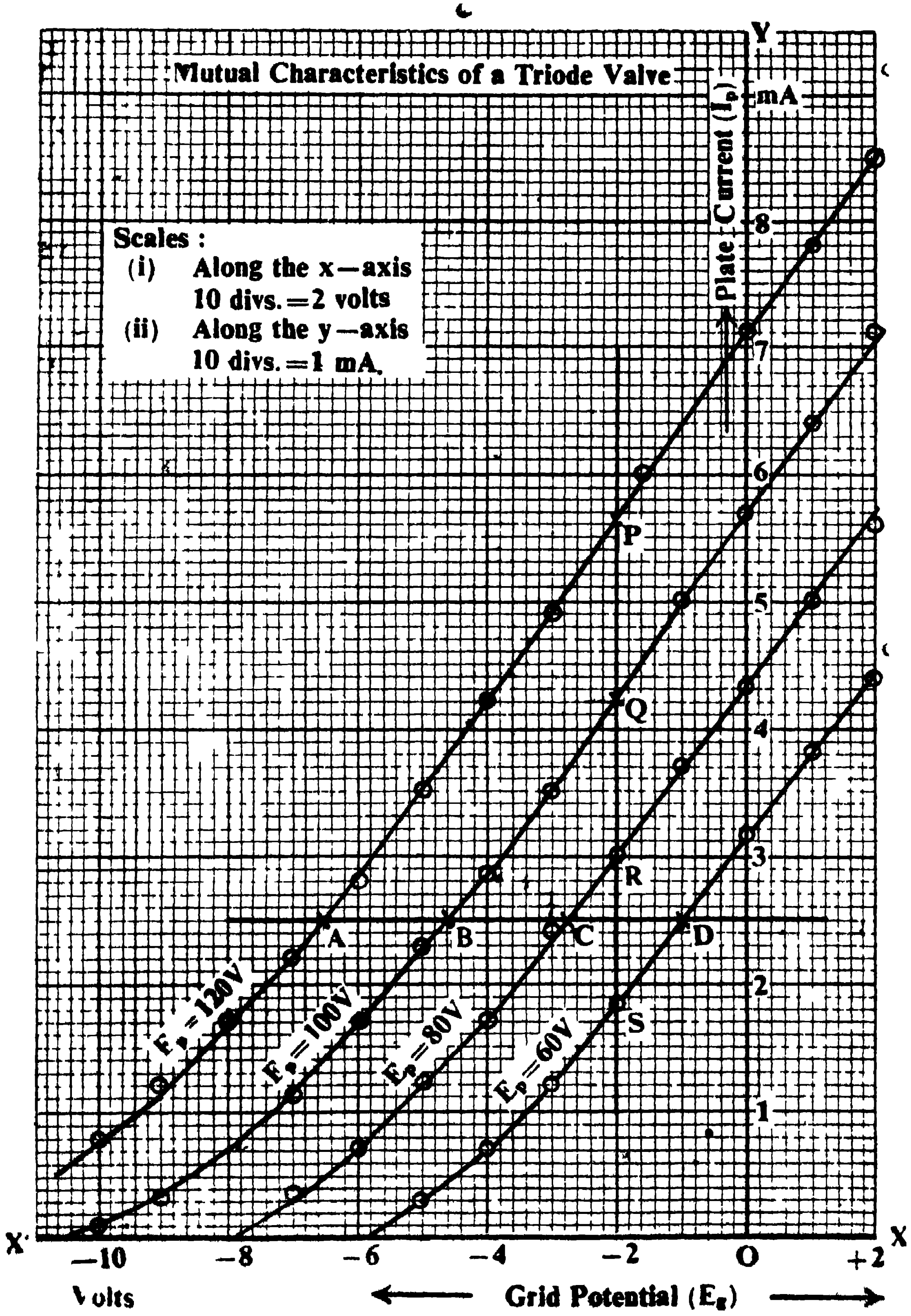
Mutual Characteristics of a Triode Valve
Scales :
(i) Along the x—axis 10 divs.=2 volts
(ii) Along the y—axis 10 divs.=1 mA.
Y
Plate Current (I_p)
mA
8
7
6
5
4
3
2
1
P
Q
R
S
A
B
C
D
E_p=120V
E_p=100V
E_p=80V
E_p=60V
X'
X
−10
−8
−6
−4
−2
O
+2
Volts
Grid Potential (E_g)

Fig. 93