CAMBRIDGE ALTERNATING CURRENT INSTRUMENTS

FOR HIGH FREQUENCIES

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INTRODUCTION

THE development of wireless telegraphy has been responsible for the growth of many instruments designed to measure the constants of high frequency circuits. In the design of the apparatus included in this catalogue, we have again received generous help from scientific men; this close co-operation between the scientist and the manufacturer has enabled each piece of apparatus to be designed so as to perform its particular function in the most efficient way, whether it be employed in the testing laboratory, where a high degree of accuracy and sensitivity is essential, or used in connection with the many commercial tests now required by the electrical engineer. The name of Mr. A. C. Campbell, late of the National Physical Laboratory, must be particularly mentioned in this connection, as he is entirely responsible for the design of a number of instruments dealt with in the catalogue, which have made for themselves a world-wide reputation.

Some novel instruments having many industrial as well as scientific applications are described in the catalogue, the most striking being the Rectifier Voltmeter due to Mr. E. B. Moullin. In this voltmeter, a triode valve is used as a rectifier, and the rectified current, produced either by the curvature of the anode current/grid potential characteristic or by the curvature of the grid current/grid potential characteristic, is used to measure the applied electromotive force by means of a galvanometer. For low voltages (0 to 10 volts), the voltmeter is about forty times as sensitive as the best commercial electrostatic voltmeter; it has an accuracy equal to that of a vacuum thermo-junction, and, as an ammeter, approximately thirty times its sensitivity. In addition, the instrument possesses the outstanding advantages that it absorbs no power from the circuit, its readings are independent of frequency, and it cannot be injured by an overload.

The importance of having a current of true sine wave-form for high frequency test work, has led to the development of the Valve Generator (described on page 15). Utilising, as it does, a triode valve, the frequency and amplitude of the current generated remain constant as long as the conditions do not vary, and the frequency can be easily and accurately adjusted over a wide range. In a somewhat similar generator, suggested by Professor W. H. Eccles and Mr. Jordan, the time of oscillation of the circuit is controlled by a tuning fork. A third form of generator—the Reed Hummer—gives oscillations of audio-frequency suitable for bridge-testing. This Hummer has been developed by the Engineering Research Section of the British Post Office; it is embodied in the Trunk Cable Capacity Test Set manufactured by us to its design and specification. By the courtesy of the Chief Engineer, a short description of this apparatus is included in the catalogue.

The question frequently arises as to the relative sensitivities of the various combinations of galvanometers and thermo-junctions which can be used for high frequency current measurements, and Tables Nos. X., XI. and XV. have been compiled in the hope that they may be of service to our customers in this connection. Up to the present, the information contained in these tables has not been readily available.

The catalogue has been divided into two parts, the first part containing brief descriptions of the instruments themselves, while in the second part various methods of using these instruments for high frequency measurements are described in some detail.

Descriptions of other instruments made by us for alternating current work will be found in List 161, "Alternating Current Measuring Instruments for Supply Frequencies."

INDUCTANCE STANDARDS

AND ACCESSORIES

Campbell Variable Mutual Standard.[1]

This instrument (illustrated in Fig. 1), used in conjunction with its auxiliary apparatus, provides one of the most accurate and direct means of measuring inductance and capacity. One of its chief advantages is that its value can be varied through zero, with the result that quite small capacities and inductances can be accurately determined.

The design, incorporating two decade dials and a long proportioned scale, enables accurate readings to be obtained. For example, on the 11-millihenry instrument a value of mutual inductance such as 8673·2 microhenries can be set directly to the last unit, and by estimation to the decimal part ; again, owing to the openness at the lower end of the scale, a reading such as 2·45 microhenries may be taken on the same instrument.

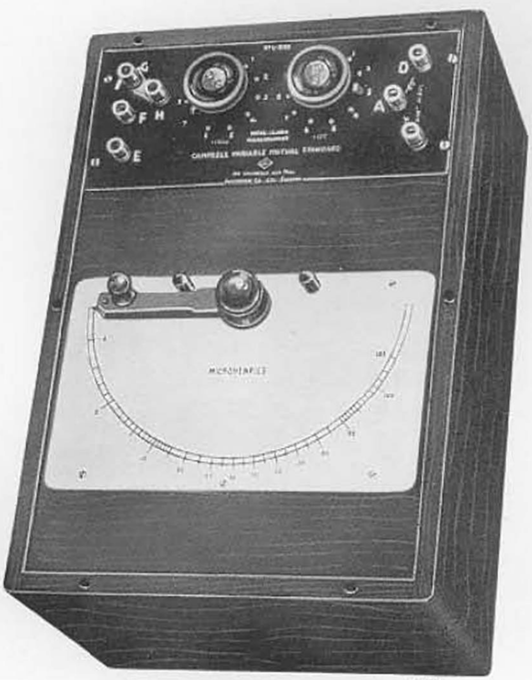

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Fig. 1

35·5 × 25·5 × 22·5 cm. 6·5 kg.

The range of the instrument is large, the value of the movable coil extending from minus 3 to 104 microhenries, whilst the two dials give 100, 200, 300 . . . 1000, and 1000, 2000, 3000 . . . 10,000 microhenries respectively. The scale has a length of 300 mm., but the dials have the effect of increasing this to an equivalent length of 30,000 mm.

The principle of the instrument will be understood by referring to Figs. 2 and 3 illustrating the construction of the 11-millihenry Standard. The primary circuit consists of two equal coaxial coils P and P_1, wound in the same direction and connected in series, the ends being brought out to terminals on the right-hand side of the ebonite board ; the exact centre point of the primary is connected to the middle terminal **a** on the right. The secondary consists of three circuits, which can be put in series :—(1) The movable secondary S, which can be turned about an eccentric axis, by means of a pointer fixed to this axis and moving over a semi-circular scale ; (2) the fixed secondary A, wound on the lower bobbin and subdivided into ten equal sections, which are connected in series, their junctions being brought to an 11-stud switch dial ; and (3) a fixed secondary B, stranded similarly to A, wound on the upper and lower bobbins and connected to another dial. The fixed secondaries A and B are connected in inductive series between the terminals E and H, whilst the movable secondary is connected between F and G. When the terminals G and H are connected by the link provided, the mutual inductance of the movable secondary adds to that of the fixed secondaries. If the link is changed to F and H, the movable secondary is reversed, thus enabling the 100 on the scale to be checked against the first section of the fixed secondary B. All the coils are wound of highly stranded wire, and the use of metal parts adjacent to the coils has been avoided. The effects of distributed capacity have been reduced to a minimum,

[1] A Campbell, *Phys. Soc. Proc.*, 1908, xxi. 69 ; and *Phil. Mag.*, 1908, xv. 155.

INDUCTANCE STANDARDS

AND ACCESSORIES—*continued*

so that, even at a frequency of 1000 cycles per second, the correction is only one part in a thousand. A curve can be supplied, if required, showing the frequency error when this instrument is used for frequencies up to 2000 periods per second. The primary will carry 0·6, and the secondary 0·8 ampere. The self inductance of the primary, which is usually about 23 millihenries, is engraved on the instrument; also its resistance, which is adjusted to 14 ohms. For very accurate tests the instrument may be fitted with a tube for the insertion of a thermometer.

In the bridge measurements of self inductance (described in Part II.) it is a great convenience to have the zero of the bridge at the zero reading of the Variable Mutual Standard, and to secure this the self inductances in the two inductance arms must have the same ratio as the resistances of the ratio arms. In the case of equal ratio arms, this is accomplished by including half the primary winding of the Standard in each of the arms, and it is for this reason that the centre point of the primary winding is brought out to a terminal. The range of the equal ratio bridge may be extended by the introduction of suitable self inductances in the left-hand inductance arm (arm *AB*, Fig. 65, page 41). A 20-millihenry coil used with an 11-millihenry Standard in this way will extend the range up to 40 millihenries.

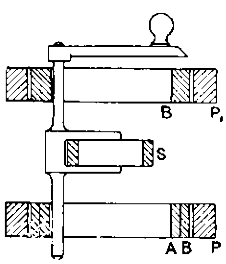

Fig. 2

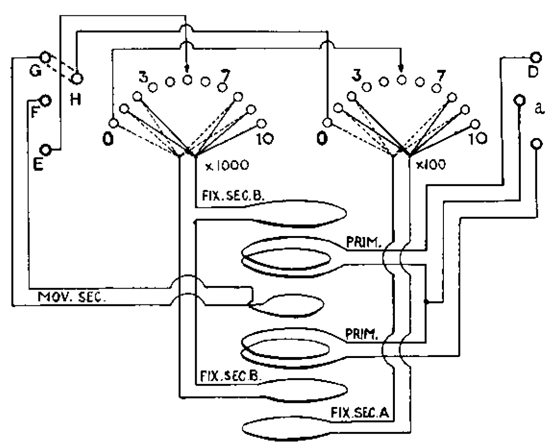

Fig. 3

When the ratio arms are unequal, separate balancing coils are introduced, having inductances 1/9th and 1/99th of the primary winding. The range of the 11-millihenry Variable Mutual Standard, when used with unequal ratio arms 1 : 99, is extended to 1·1 henries.

In addition to the 11-millihenry Standard described above, Standards of lower and higher values are made, being suitable respectively for measurements of the small inductances and capacities used in radio transmission and of the large inductances used in electrical engineering.

Cat. No.	
47211	**Campbell Variable Mutual Standard,** range from minus ·00003 millihenry to 1·1 millihenries, or, with multiplying ratios, to 0·11 henry.
47212	**Ditto,** range from minus ·0003 millihenry to 11 millihenries, or, with multiplying ratios, to 1·1 henries.
47213	**Ditto,** range from minus ·002 millihenry to 110 millihenries, or, with multiplying ratios, to 11 henries.
47216	**Set of two Balancing Coils,** for Standard Cat. No. 47211.
47217	**Ditto,** for Standard Cat. No. 47212.
47218	**Ditto,** for Standard Cat. No. 47213.

Campbell Inductometer Bridge.

This bridge, (illustrated in Fig. 4), comprises a simplified form of variable mutual inductance with a pair of self-contained noninductive ratio arms, 10 : 10 ohms. It is useful for many measurements where the high accuracy given by the Campbell Variable Mutual Standard is not required, and enables a large range of methods to be demonstrated in the laboratory.

The inductometer consists of fixed primary and movable secondary coils, the latter being so shaped as to give a nearly uniform scale. The whole of the inductance variation is read on the scale, the range of which can be varied in the ratios 1, 2, 5, 10, 20, 50 and 100. The primary is divided in the centre, as in the case of the Variable Mutual Standard, so that no balancing coils are required when the equal ratio arms are in use. By introducing balancing coils, the instrument can be used for the measurement of large inductances. By adding a suitable low-induction resistance box, source, and detector, the apparatus becomes a complete Heaviside equal-ratio bridge.

The primary is capable of carrying a current of 3 amperes on the ×1 range, or 1 ampere on the ×10 range, and the secondary will safely carry 1 ampere.

The scale of the inductometer has an approximate length of 300 mm., and the standard range is from minus 0·5 to 10·5 microhenries. This low range is particularly useful for measurements of residual inductances of resistance coils, leads, etc.

The maximum mutual inductance is 1 millihenry. The range of measurement of self inductance can be increased up to 100 millihenries by using unequal ratio arms.

The bridge can be used for capacity measurements by the Carey Foster method (see Part II., page 42), for which purpose a special auxiliary box is made (see page 7). With this addition, it is possible to measure capacities from 10 micro-microfarads up to 1 microfarad.

In addition to the standard instrument described above, an Inductometer Bridge can be supplied with noninductive ratio arms 1000 : 1000 ohms. Instruments can also be made up having other ranges, reading, for example, to 1 microhenry or to 100 microhenries on the scale.

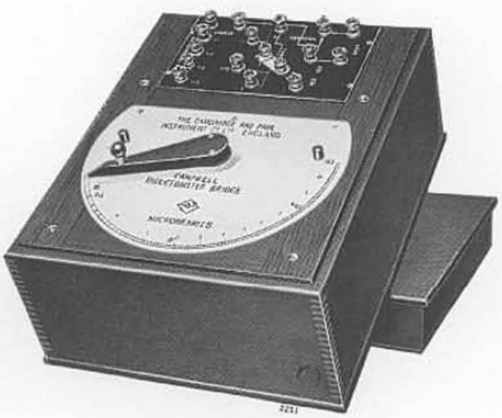

Fig. 4

31·0×25×16·3 cm. 3·4 kg.

Cat. No.	
47221	**Campbell Inductometer Bridge,** with ratio arms 10 : 10 ohms, reading from minus 0·5 microhenry to 1 millihenry, or, with multiplying ratios, to 100 millihenries.
47226	**Set of two Balancing Coils,** adjusted to 1/9th and 1/99th of inductance of primary of above.
47222	**Campbell Inductometer Bridge,** with ratio arms 1000 : 1000 ohms, reading from 50 microhenries to 100 millihenries, or, with multiplying ratios, to 10 henries.
47227	**Set of two Balancing Coils,** adjusted to 1/9th and 1/99th of inductance of primary of above.

Carey Foster Auxiliary Box for use with Campbell Variable Mutual Standard.

In the measurement of capacity by Carey Foster's method,[1] adjustable resistance arms R and P are required (see Part II., page 42). In the auxiliary box, (see Fig. 5), these resistances are put up in a form which enables readings to be interpreted directly in microfarads or in micro-microfarads, by the aid of simple multipliers. The resistance of the primary of the Variable Mutual Standard is allowed for in the adjustment of the arm P; the auxiliary box must therefore be adjusted to suit the type of Standard with which it is used. The provision of terminals with a link in the P arm enables additional self inductance to be applied when measuring poor dielectrics and condensers. As will be seen from Table No. I., a great range of capacities can be measured by this method.

If the 1·1-millihenry Standard (Cat. No. 47211) is used, the figures in the last column must be divided by 10. They must be multiplied by 10 if the 110-millihenry Standard (Cat. No. 47213) is employed.

In making accurate tests, it is necessary to allow for the resistance temperature coefficient of the copper portion of the P arm.

[1] G. Carey Foster, *Phil. Mag.*, 1887, xxiii. 121.

INDUCTANCE STANDARDS

AND ACCESSORIES—*continued*

TABLE No. I.

Carey Foster Auxiliary Box used with Standard. Cat. No. 47212.

Value of P.	Value of R.	Multiplier $= \frac{1}{PR}$	Maximum Capacity. Measurable in Microfarads.
100	10	1×10^{-3}	11·1
200	10	5×10^{-4}	5·55
100	50	2×10^{-4}	2·22
200	50	1×10^{-4}	1·11
200	100	5×10^{-5}	0·555
500	50	4×10^{-5}	0·444
500	100	2×10^{-5}	0·222
100	1000	1×10^{-5}	0·111
200	1000	5×10^{-6}	0·0555
500	1000	2×10^{-6}	0·0222
1000	1000	1×10^{-6}	0·0111

Wagner Earthing Device.

In the accurate measurement of small condensers, as used in radio-telegraphy, it is important to take account of earth capacities particularly when measuring energy losses. The earthing device due to Wagner[1] eliminates earth effects from the salient parts of a bridge by bringing the detector virtually to earth potential without actually earthing any point on the bridge.

The addition of an earth potential connection and a switch enables a modification of the Wagner Earthing Device[2] to be used with the Carey Foster Auxiliary Box (see Fig. 5).

A variable self inductance and a variable resistance, which are adjustable to be equal to the self inductance of the primary of the Standard and to the resistance R of the bridge respectively, are connected in series across the source, and their common point is earthed. An approximate balance is first obtained with normal connections; a subsidiary balance is then obtained with the telephone between the earthed point and one of the bridge points, to which its ends are normally connected. The end of the telephone is thus brought to earth potential, and hence the whole telephone and leads are at earth potential when the bridge balance is obtained. A final balance is then obtained with normal connections.

Auxiliary boxes which are not fitted with the earth potential connection and switch, shown in Fig. 5, can easily have these added.

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Fig. 5

24·4×13·2×18·8 cm. 2·7 kg.

Carey Foster Auxiliary Box for use with Inductometer Bridge.

This box is similar to, but simpler than that shown in Fig. 5. The arm R contains resistances 10 and 100 ohms; the arm P, 100 and 1000 ohms. The resistance of the primary of the inductometer is allowed for in the adjustment of the latter arm, and the auxiliary box is therefore adjusted to suit the individual inductometer bridge with which it is to be used. Readings are obtained directly in microfarads or micro-microfarads by the aid of simple multipliers, the ranges provided being given in Table No. II.

TABLE No. II.

Value of P.	Value of R.	Multiplier $\frac{1}{PR}$	Maximum Capacity. Measurable in Microfarads.
100	10	10^{-3}	1
100	100	10^{-4}	0·1
1000	10	10^{-4}	0·1
1000	100	10^{-5}	0·01

Cat. No.	
47231	**Carey Foster Auxiliary Box** for use with Campbell Variable Mutual Standard. Cat. No. 47211.
47232	**Ditto,** for Standard. Cat. No. 47212.
47233	**Ditto,** for Standard. Cat. No. 47213.
47235	**Carey Foster Auxiliary Box** for use with Inductometer Bridge. Cat. No. 47221.
47236	**Ditto,** for Cat. No. 47222.
47239	**Wagner Earthing Device.**

[1] K. W. Wagner, *Elektrotech. Zeits.*, 1911, xxxii. 1001; also *Electrician*, 1911, lxviii. 483.
[2] D. W. Dye, *Electrician*, 1921, lxxxvii. 55; and N.P.L. Annual Report, 1920, 62.

INDUCTANCE STANDARDS

AND ACCESSORIES—*continued*

Campbell Standard Subdivided Mutual Inductances.

Fig. 6
22·5×31·3×11·3 cm. 2·7 kg.

These inductances (see Fig. 6) consist of primary and secondary concentric coils wound on the same bobbin in the same mean plane. The coils are well insulated from one another, and the secondary coil is divided, by stranding, into 10 circuits connected in series. The junctions are brought out to a 10-point switch, so that the value of the inductance in the circuit can be varied. Highly stranded wire is used for the coils, and care is taken to reduce to a minimum capacity in the windings which would cause errors at high frequencies. The use of metal near the coils has been avoided, and the instrument can be recommended for use as a standard of mutual inductance for frequencies up to 2000. It is suitable for telephone work.

Cat. No.
47251 **Campbell Standard Subdivided Mutual Inductance,** giving steps 0, 0·1, 0·2, 0·3 . . . 1·0 millihenry.
47252 **Ditto,** giving steps 0, 1, 2, 3 . . . 10 millihenries.

Simple Mutual Inductance Coils.

An accurately known mutual inductance affords one of the best methods of calibrating a ballistic galvanometer. If its value is M henries, a current of I amperes flowing in the primary coil will give a flux linkage of $10^8 MI$ line-turns in the secondary. For ordinary galvanometers suitable values of M are 1 or 10 millihenries, giving respectively 10^5 and 10^6 line-turns per ampere of primary current.

Approximate data for these inductances are given in Table No. III.

TABLE No. III.

Cat. No.	Mutual Inductance (Millihenries).	Line-turns per Ampere.	Maximum Current (Amperes).	Approximate Resistance (Ohms). Primary.	Approximate Resistance (Ohms). Secondary.
47261	10	10^6	1	5	22
47262	1	10^5	10	0·04	22
47263	0·1	10^4	10	0·02	0·3
47264	0·01	10^3	10	0·012	0·1

Self Inductance Standards (Single Range).

These coils (see Fig. 7) are accurately adjusted to a stated self inductance. They are made up either with highly stranded wire (series A), in which each strand is separately insulated, or with solid wire (series B). In both forms the coils are wound on substantial bobbins of mahogany. The metal parts are reduced to a minimum to avoid changes in effective resistance.

Fig. 7

Cat. No.
47271 **Self Inductance Standard (Single Range), Series A.** Wound for 1, 10, 20, 40, 100 or 1000 millihenries.
47272 **Self Inductance Standard (Single Range), Series B.** Wound for 1, 10, 20, 40, 100 or 1000 millihenries.

Standard Self Inductances for Radio Frequencies.

These inductances are designed to give minimum self-capacity, and are wound with highly stranded wire. They are accurately adjusted to definite values in microhenries, from 8 microhenries upwards. Coils up to 500 microhenries are wound in a single layer on ebonite bobbins, or on discs, as desired. The distributed capacity in their windings is reduced to a minimum, and their values are therefore independent of frequency. The coils of value 1 to 20 millihenries are slice-wound with space windings, to give small decrement and small self-capacity. Coils of any desired inductance can be supplied.

The illustration (Fig. 8) shows a self inductance for 12,800 microhenries.

Fig. 8
22·4 × 22·4 × 6·8 cm. 1·2 kg.

Cat. No.
47276 Standard Self Inductance for Radio Frequencies.

Self Inductance Standard, Multi-range Compensated Type.

Fig. 9
31·3 × 22·5 × 15 cm. 4·7 kg.

A useful multi-range inductance has been designed for making measurements of inductance or capacity, in which it is necessary to vary the value of the self inductance without altering the resistance of the bridge arm. In this instrument, illustrated in Fig. 9, a noninductive copper coil of equal resistance is substituted for each portion of the inductance that is cut out. This is effected automatically by the dial switch. Ten steps of inductance are provided, the magnitude of each step being adjusted according to requirements. The resistances and inductances are adjusted at 800 cycles unless otherwise ordered.

These self inductance standards are supplied for three ranges :—

Cat. No.
47281 Self Inductance Standard, Multi-range Pattern, with steps 0, 1, 2, . . . 10 millihenries.
47282 Ditto, 0, 10, 20, . . . 100 millihenries.
47283 Ditto, 0, 100, 200, . . . 1000 millihenries.

Variable Self Inductances.

These are of the Mansbridge type, and consist of an ebonite disc which carries two "D" shaped coils wound with stranded wire, which can rotate over another disc carrying a second pair of similar coils. Terminals are provided to give a series of ranges from 0·7 to 105 millihenries. A paralleling switch enables the scale to be halved in range.

Cat. No.
47291 Variable Self Inductance.

LOW INDUCTION RESISTANCES

Low Induction Decade Resistances for Alternating Currents.

Fig. 10
24×26·5×17·5 cm. 3·7 kg.

The ordinary type of resistance box is unsuitable for use with alternating currents, because the low resistance coils have appreciable inductance, and the higher resistance coils have considerable capacity. The forms of winding adopted in the resistance box shown in Fig. 10, by which inductance and capacity effects are practically eliminated, were developed independently by Campbell at the National Physical Laboratory[1] and by Grover and Curtis at the Bureau of Standards.[2] The effectiveness of the construction will be seen from the following table :—

TABLE No. IV.

Resistance (Ohms).	Inductance (Microhenries).	Time Constant.
0·1	0·003	$0{\cdot}03 \times 10^{-6}$
1	0·02	$0{\cdot}02 \times 10^{-6}$
10	0·1	$0{\cdot}01 \times 10^{-6}$
100	0·1	$0{\cdot}001 \times 10^{-6}$
1000	1	$0{\cdot}001 \times 10^{-6}$

It will be noted that these resistance boxes are suitable for frequencies up to 1000 or 2000 per second. The safe continuous loading is about 0·5 watt per coil. The resistances are adjusted to an accuracy of one part in one thousand. The switch contacts are internal, being thus protected from dust, and have a resistance of only about 0·0005 ohm. The coils are well aged, impregnated with shellac and covered with paraffin wax to reduce the risk of variation of capacity with humidity.

Cat. No.
43251 **Low Induction Decade Resistance Box,** with 4 dials: tenths, units, tens and hundreds.
43252 **Ditto,** with 4 dials: units, tens, hundreds and thousands.

Low Induction Ratio Box.

The ratio box, illustrated in Fig. 11, is intended for use with the Decade Resistance Box described above, or when measuring small self inductances, effective resistance, and capacity (see Part II.). The resistances are so constructed that their small residual inductances bear the same ratio as their resistances, which have the following values:—
900, 90, 10 : 10, 90, 900.

By a suitable arrangement of the plugs, equal ratio arms 10 : 10, 100 : 100, 1000 : 1000, or unequal ratio arms 1000 : 100, 1000 : 10, 100 : 10, can be obtained, as required for the Wheatstone Bridge. When used as described in Part II. (page 41), however, the plugs are arranged to give the ratios 90 : 10, 900 : 100, 990 : 10, corresponding to multipliers of 10, 10 and 100.

A similar ratio box is also constructed having coils one-tenth of the above-mentioned values, this box being better adapted for use in conjunction with lower resistances. Both the above ratio boxes are supplied in a shielded pattern.

Fig. 11
22·5×10×21 cm. 1·5 kg.

Cat. No.
43253 **Low Induction Ratio Box, shielded pattern**—900, 90, 10 : 10, 90, 900.
43254 **Ditto,** 90, 9, 1 : 1, 9, 90.

[1] A. Campbell, *Roy. Soc. Proc.*, 1912, lxxxvii. 391.
[2] F. W. Grover and H. L. Curtis, *Bureau of Standards Bull.*, 1912, viii. 455.

LOW INDUCTION RESISTANCES

Continued

Low Induction Variable Ratio.

This ratio box is suitable for use in any high frequency tests involving the use of a continuously variable ratio, and more particularly for the Wien and Hay measurements of capacity and inductance (see Part II., pages 45 and 46). It contains a fixed and also a variable arm; the fixed arm can be set alternatively to one hundred or to one thousand ohms. The variable arm comprises four sets of coils—hundreds, tens, units and tenths—controlled by switches. In series with these coils is a low induction sliding rheostat giving hundredths and thousandths of an ohm. The total resistance of this arm is 1111·1 ohms; the whole is designed to have negligible inductance and capacity.

Cat. No.
43257 **Low Induction Variable Ratio.**

Campbell Constant Inductance Resistance Box.

In measuring small inductances, it is necessary to use an adjustable resistance which will introduce no error by its own inductance or capacity, unless the residual inductance of the adjustable resistance is known.

Fig. 12
45 × 20 × 17·5 cm. 5·8 kg.

In the instrument shown in Fig. 12, the resistance coils have an extremely low residual inductance, which is compensated for by substituting a copper winding of equal inductance for each resistance coil cut out of the circuit. Since the resistance box is intended for use in tests in which a preliminary balance is obtained, and the result is given in the form of the difference between two readings, these copper windings do not enter into the calculation. The compensating windings for the set of ten unit coils have a total resistance of only 0·01 ohm, and for the set of tens and hundreds, of 0·2 ohm per dial. The compensating windings are automatically put into circuit by the movement of the resistance switch, which is provided with a double circle of contact studs.

Cat. No.
43291 **Campbell Constant Inductance Resistance Box,** with three dials, units, tens and hundreds (total resistance 1110 ohms); in case, with detachable cover.

Campbell Constant Inductance Rheostat.

Fig. 13
28 × 29 × 7·5 cm. 4·1 kg.

This rheostat, illustrated in Fig. 13, is constructed on the same general principle as the resistance box just described. The resistance wire and a copper compensating wire are wound in parallel grooves round the edge of an insulating disc. The contact and terminals are so arranged that as the arm is moved up the scale, just enough copper is cut out of the circuit to compensate for the additional inductance added; the inductance is thus kept constant. The return lead is wound round the circumference between the resistance and the copper wires, thereby reducing the actual inductance to a minimum.

Potential terminals are fitted to enable the rheostat to be used in certain bridges requiring a potential point. A cover can be provided.

Cat. No.
43292 **Campbell Constant Inductance Rheostat,** range 0·05 ohm to 1·2 ohms.
43293 **Ditto,** range ·005 ohm to 0·12 ohm.
43294 **Cover** for above.

CONDENSERS

Fig. 14
17·5 × 17·5 × 13·5 cm. 2·2 kg.

Precision Mica Condensers.

These condensers are built up with the finest ruby mica plates, precautions being taken to ensure perfect contact between the surfaces; the connections are soldered throughout. The smallest capacities are adjusted by the Carey Foster method (see Part II., page 42) to a high degree of accuracy, the larger capacities to about 0·01 per cent. The temperature co-efficient is only about 0·04 per cent. per degree Centigrade. The condensers are tested with 2000 volts alternating pressure during manufacture, and are therefore suitable for a working pressure of 500 volts A.C. The dielectric losses in condensers constructed on this principle are extremely low, the phase displacement being usually between 30 and 60 seconds of arc at 1000 cycles, corresponding to a power factor of ·0002.

Single Mica Condensers.

Single condensers from ·001 to 0·1 microfarad are mounted between stabilit plates with terminals. From 0·1 to 2 microfarads they are sealed in stout metal cases, thus preventing variation due to changes in barometric pressure, and the whole is enclosed in an external brass case with ebonite top fitted with short-circuiting plug (see Fig. 14). Condensers from ·001 to 0·1 microfarad can also be supplied in shielded cases if required.

Fig. 15
16 × 20 × 13 cm. 4 kg.

Cat. No.

47315 **Single Mica Condenser,** mounted between stabilit plates. ·001, 0·01, 0·02, 0·05, or 0·1 microfarad.

47316 **Ditto,** in shielded case.

47317 **Single Mica Condenser,** in sealed metal case, 0·1, 0·33, 0·5, 1 or 2 microfarads.

Fig. 16
44 × 15 × 17 cm. 5 kg.

Subdivided Mica Condensers.

Subdivided condensers are each contained in a sealed metal case which is enclosed in a mahogany box with ebonite top. Plug blocks can be provided for putting the sections in circuit (see Fig. 15), or decade mica condensers can be supplied with one or more dials, having ten sections of ·001, 0·01, 0·1 microfarad; a condenser of this type is illustrated in Fig. 16.

TABLE No. V.
Subdivided Mica Condensers.

Cat. No.	Type of Switch.	Total Microfarads.	Subdivisions.
47321	Plug	0·11	·001, ·002, ·002, ·005, ·01, ·02, ·02, ·05.
47322	,,	0·55	·05, 0·1, 0·2, 0·2.
47323	,,	1	0·1, 0·2, 0·2, 0·5.
47324	,,	1·05	·05, 0·1, 0·2, 0·2, 0·5.
47326	Laminated Brush.	1·11	10 × ·001, 10 × ·01, 10 × 0·1.

CONDENSERS

Continued

Paper Condensers, Telephone Type.

These condensers are similar to those supplied for telephone work, but are more finely adjusted. They are tested at 350 volts continuous pressure; if the insulation should break down by a temporary rise of pressure, the perforation usually seals up automatically. The capacity is adjusted to be correct to about 2 per cent. at 800 periods per second.

Fig. 17
18 × 15 × 10 cm. 1·8 kg.

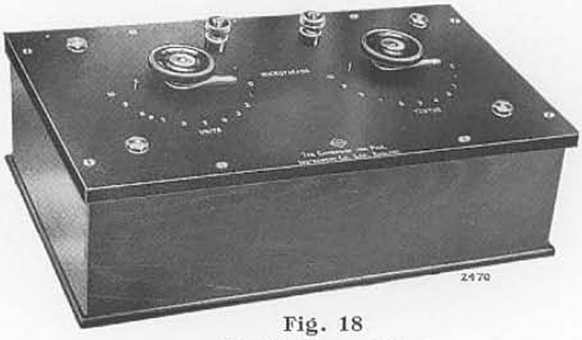

Fig. 18
30·5 × 16 × 12 cm. 3·8 kg.

Single condensers can be supplied in metal cases with tag terminals. They are made in capacities from 0·1 to 10 microfarads. Similar condensers are mounted in mahogany cases with terminals mounted on an ebonite board.

Cat. No.
47331 **Single Paper Condenser, Unmounted,** 0·1, 0·2, 0·5, 1, 2, 5 or 10 microfarads.
47332 **Single Paper Condenser, Mounted,** 0·1, 0·2, 0·5, 1, 2, 5 or 10 microfarads.

The subdivided condensers, as illustrated in Fig. 17, are fitted with key switches to each section. In one position of the switch the section is "in," and by turning the switch it is cut out and short-circuited.

Decade condensers, as Fig. 18, are made with one or more dials, each containing ten sections. The sections are controlled by a paralleling switch. This form is most generally useful, and is particularly suitable for tuning circuits where continuous and rapid variation of capacity is often required.

TABLE No. VI.

Subdivided Paper Condensers, Telephone Type.

Accuracy 2 : 100.

Cat. No.	Style of Switch.	Total Micro-farads.	Subdivisions.
47341	Key	10	5 × 2
47342	,, ...	50	5 × 10
47343	,, ...	10	0·5, 0·5, 1, 4 × 2
47344	,, ...	1·05	·05, 0·1, 0·2, 0·2, 0·5
47345	,, ...	10·5	0·5, 1, 2, 2, 5
47346	Laminated Brush	1	10 × 0·1
47347	,, ,,	10	10 × 1
47348	,, ,,	11	10 × 0·1 10 × 1
47349	,, ,,	111	10 × 0·1, 10 × 1, 10 × 10

Paper Condensers, Power Type.

These condensers have the same general characteristics as those already described, but have considerably greater dielectric strength. They are suitable for continuous use on circuits up to 550 volts alternating; the insulation resistance is high, being over 5000 megohms per microfarad. The electrodes have a low resistance, and will carry currents up to 5 amperes. Each condenser is tested with 2000 volts alternating pressure, and possesses the valuable property of sealing automatically if the insulation is accidentally broken down. The power factor is about 0·013 at 1000 cycles. The condensers are made up in units of 1 microfarad, hermetically sealed in metal cases fitted with small screw terminals. They can also be supplied mounted in mahogany cases, with terminals mounted on ebonite. Subdivided condensers are constructed by mounting several units in a mahogany case, the sections being connected to plug blocks mounted on an ebonite board.

Cat. No.
47351 **Single Unmounted Power Type Condenser,** 1 microfarad.
47352 **Single Mounted Power Type Condenser,** 1, 2, 5 or 10 microfarads.
47356 **Subdivided 10-microfarad Power Type Condenser**, sections of 1, 2, 2 and 5 microfarads.

CONDENSERS

Continued

Fixed Plate Condensers.

These condensers, illustrated in Fig. 19, are constructed of aluminium plates with an air-space between them; they are enclosed in vessels which can be filled with oil. They are suitable for use in wave-meters as well as in many methods of capacity measurement, including the determination of the dielectric constants of various materials. They are also suitable for use in radio-telegraphic receiving circuits.

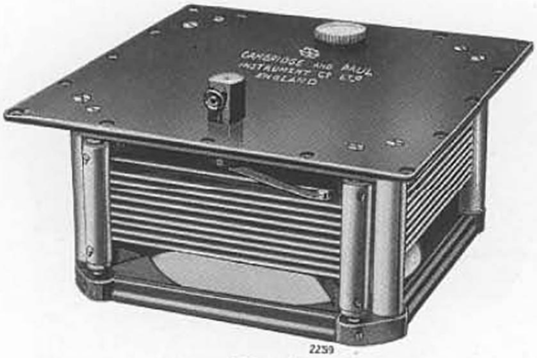

Fig. 19
19·5 × 18 × 12 cm. 3·3 kg.

Each set of aluminium plates is held in a separate frame, the two frames being insulated from each other by amberite blocks. An aluminium cover forms part of the outer of the two frames, and has a tubular pillar at each corner. Slots are cut in these pillars, into which the corners of the plates fit tightly. The other set of plates is similarly held, and can be set relatively to the first, so that the air gaps are equal. A well-insulated terminal makes connection to the latter set; the whole condenser is contained in a stout copper tank.

The condensers can be stood one upon each other in order to build up a capacity which shall be exactly equal to the sum of the separate sections. In such cases, the bottom of each tank is provided with four feet, one of which has a conical recess, another a V-groove, and the others plane surfaces. These feet fit on rounded studs on the top of the condenser below. The terminals are brought out horizontally to permit of stacking the condensers in this manner.

The tank may, alternatively, be constructed so that the condenser can be stood on its side without spilling, and, when necessary, ebonite battens may be fitted to insulate it from its support. These condensers can be built to any required capacity. The specimen illustrated has nine plates, with an active surface of about 12·5 × 12·5 cm. on each side, and they are spaced about 1 mm. apart. The approximate capacity in air is ·0006 microfarad, or in oil three or four times this value.

Cat. No.	
47361	**Fixed Plate Condenser.**

Variable Plate Condensers.

These condensers (see Fig. 20) are of the well-known type having fixed semi-circular aluminium vanes, and a similar set of movable vanes attached to a central spindle. To prevent play, the spindle is provided with a long conical bearing. The distance between the electrodes is 1·2 millimetres, and the condensers will withstand a pressure of 2000 volts A.C. in air. The working parts are well insulated on ebonite. The condenser is usually shielded by a metal case connected to a terminal on the top of the instrument. This case may be filled with oil. A glass case, as shown in Fig. 20, can be supplied, if desired. The scale can be calibrated to read directly in micro-microfarads.

Fig. 20
17·5 × 17·5 × 16·5 cm. 2·5 kg.

Cat. No.	
47371	**Adjustable Plate Condenser.** Capacity ·0008 microfarad in air.
47372	**Ditto,** with scale in micro-microfarads.
47373	**Adjustable Plate Condenser.** Capacity ·0012 microfarad in air.
47374	**Ditto,** with scale in micro-microfarads.

SOURCES

AND SUBSIDIARY APPARATUS

Valve Generator.

The three-electrode valve source of alternating current for testing and measuring purposes has practically displaced all other generators, except in cases where a large current is required. Provided the conditions remain the same, the amplitude and frequency of the currents generated do not vary; the frequency can be adjusted easily and accurately over a wide range. This valve generator is the outcome of considerable research undertaken with a view to providing a suitable source for the various bridge methods of measuring capacity and inductance which are described in Part II.

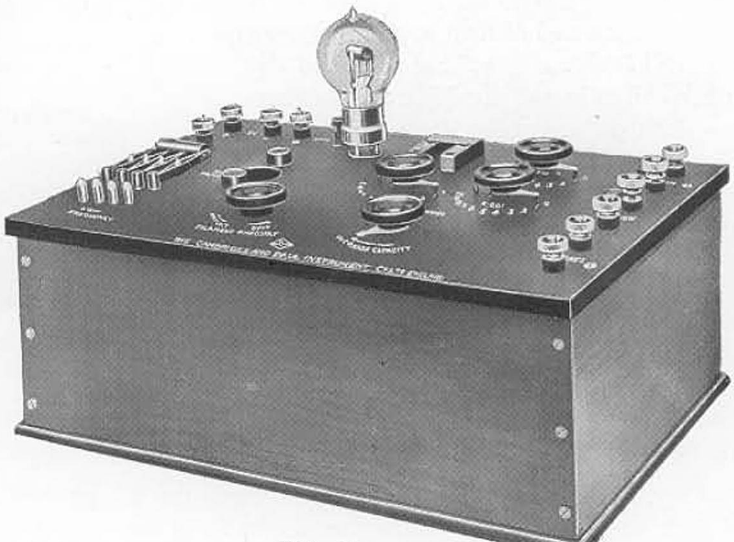

Fig. 21

41×26×19 cm. 11 kg.

The principle is indicated in the diagram (Fig. 22), where *L* and *C* are the self inductance and the set of condensers respectively which form the oscillatory circuit, the resonant frequency of which approximately governs the frequency given to the oscillations. Closely coupled to the self inductance *L* is a separate self inductance *N*, connected to the grid of the valve. A loosely coupled tertiary circuit serves to deliver the current to the external circuit.

In this generator, illustrated in Fig. 21, two sets of windings are employed—one set, for frequencies from 300 cycles downwards, for use with a vibration galvanometer; while the other set, for frequencies above 300 cycles, is for use with a telephone, and has been designed to give a pure wave-form. In addition, a laminated iron core is provided, which gives a lower range of frequency useful for various tests.

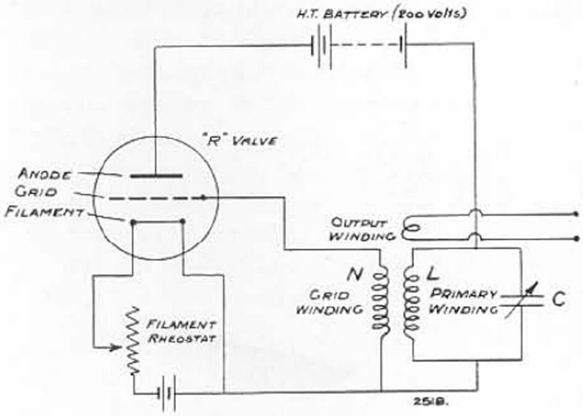

Fig. 22

The frequency is varied by altering the capacity in the oscillatory circuit. To enable the frequency to be continuously adjusted throughout the whole range, three condensers are employed, a subdivided plug-type condenser (total capacity, 3 microfarads), a 3-dial decade condenser (total capacity, 1·11 microfarads), and a variable air condenser (capacity, 0·001 microfarad). The addition of the latter condenser permits of a fine adjustment, which is a great convenience in tuning. The maximum current with a low external resistance is about 0·3 ampere. The open circuit voltage on the output winding is 20 volts.

A high-tension 200-volt battery is required for the anode circuit, and a 4-volt or 6-volt battery for the filament circuit; the current in the latter circuit is regulated by a suitable rheostat.

Cat. No.

44141 **Valve Generator,** for frequencies between 50 and 5000 cycles.

Eccles Valve-Maintained Tuning Fork.

This apparatus, designed by Professor W. H. Eccles and Mr. F. W. Jordan,[1] is illustrated in Fig. 23. It is somewhat similar to an electric bell in principle, but the contact is replaced by a three-electrode valve. The general arrangement is shown in the diagram (Fig. 24). A tuned fork *F* is solidly mounted with its prongs between polarized windings on laminated cores which are carried on two electro-magnets. One coil is connected to the grid, and the other coil is in the anode circuit. When the fork is vibrating, an electromotive force of the same frequency as that of the fork is induced in the grid coil, and impressed on the grid of the valve. This variation of voltage on the grid gives rise to variations in the anode current of the same frequency. When this current is of correct phase relation with the motion of the prong of the fork, it provides a vibromotive force in traversing the anode windings. The transformer *T* is used to separate the generated alternating voltage from the direct voltage *E*. *A* is a thermal milliammeter.

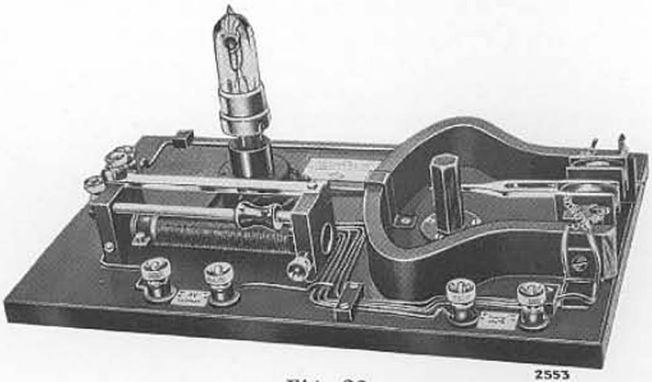

Fig. 23
20×35×9 cm. 3 kg.

The apparatus was invented and constructed for the purpose of generating voltages and currents of such amplitude and frequency as would be of use in measurements of the magnifying powers of amplifiers. For this purpose a sparkless generator is absolutely necessary, and therefore a fork sustained by means of an interrupted contact is unacceptable. The instrument described above runs steadily all day, and behaves the same day after day. It is started by switching on the voltage in the plate circuit and connecting the filament to a 4-volt cell.

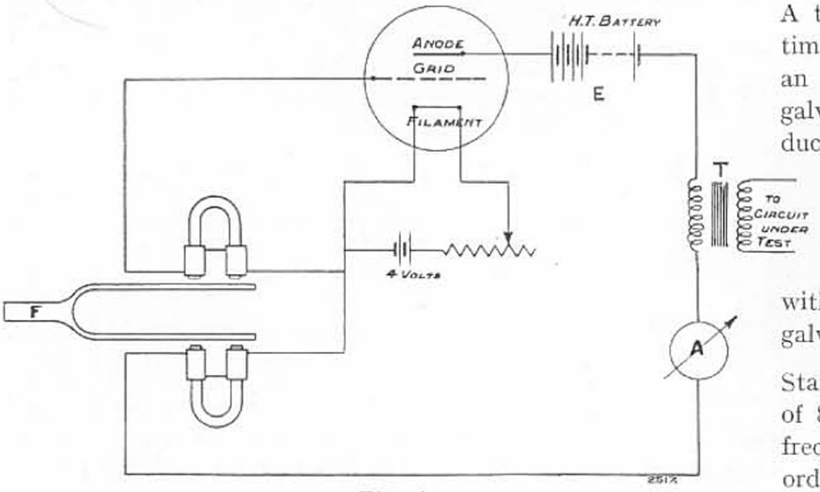

Fig. 24

A tuned fork may be used as a time marker in conjunction with an oscillograph or with a string galvanometer by placing an inductive winding on the coil in the grid or anode circuit, this winding being connected in series with an oscillograph vibrator or with the fibre of the string galvanometer.

Standard forks have frequencies of 800 or 1000, but forks of other frequencies can be supplied to order.

Cat. No.

44151 **Eccles Valve-Maintained Tuning Fork,** without high-tension battery.

44152 **High-Tension Battery.**

[1] W. H. Eccles, *Phys. Soc. Proc.*, 1919, xxxi. 269.

Reed Hummer.

The Reed Hummer (see Fig. 25) has been designed by the Engineering Research Section of the British Post Office to produce oscillations of audio-frequency used in bridge-testing. The apparatus gives an approximately pure note, and will run for hours without attention; it gives a suitable output for bridge-work. The instrument has been approved and adopted by the British Post Office for telephonic measurements; it is embodied in the Trunk Cable Capacity Test Set described on page 36.

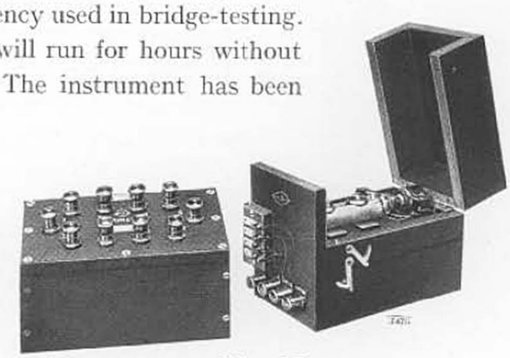

Fig. 25

21 × 11 × 15 cm. 2·9 kg.

Referring to the diagram (Fig. 26), a tuned reed *A*, which is mounted on a heavy brass base, is fixed quite near to a permanent magnet *D* which has coils wound on its pole tips; a microphone button is attached to the reed. In conjunction with a transformer *E*, two condensers, C_1, C_2, which are fitted inside the instrument case, form a tuned circuit. The reed is made to vibrate, thus setting up a disturbance in the microphone and so producing a varying current through the magnet coils which reacts on the reed and maintains it in permanent vibration. The hummer requires a battery of from 6 to 10 volts, the current taken being about 100 milliamperes. By connecting the terminals *T*, *T* to a screened transformer, an output circuit can be provided which, when connected to a bridge, prevents out of balance capacity effects at the salient points of the bridge. This transformer is supplied as a separate unit; it is shown on the left of the illustration (Fig. 25). The frequency of the hummer is approximately 1000 cycles.

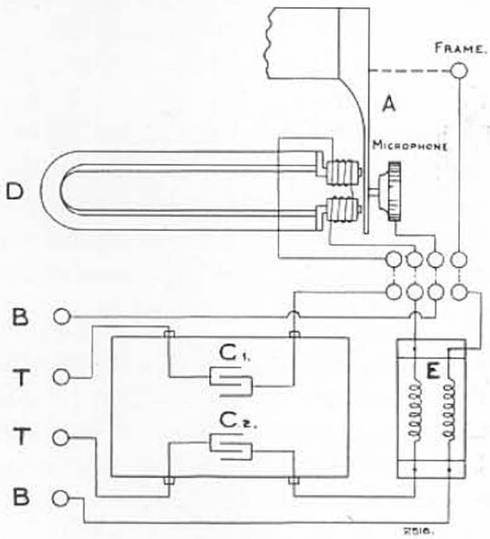

Fig. 26

Cat. No.
44153 **Reed Hummer,** without screened transformer.
44154 **Screened Transformer.**

Simple Buzzer.

This Buzzer forms an inexpensive source of alternating current for rough measurements. An electro-magnetic interrupter is used, consisting of an iron diaphragm which vibrates above the poles of an electro-magnet; the latter is periodically short-circuited through an adjustable contact on the diaphragm. The magnet and contact are joined in series with a 4-volt accumulator and the primary of a small transformer from the secondary of which an alternating current can be drawn. A screen with a terminal is provided between the primary and secondary windings. The buzzer has a frequency of 500 to 600 per second.

The buzzer and transformer are supplied in a felt-lined sound-proof box.

Cat. No.
44155 **Buzzer and Transformer.**

TUNED DETECTORS

Campbell Vibration Galvanometer.

A sensitive detector is necessary in the majority of methods of measuring capacity and inductance. This may either be a vibration galvanometer, having a movable part or element which can be so adjusted that it will vibrate in resonance with the frequency of the current which is being measured, or, alternatively, a telephone, which merely indicates and does not measure the current, may be employed.

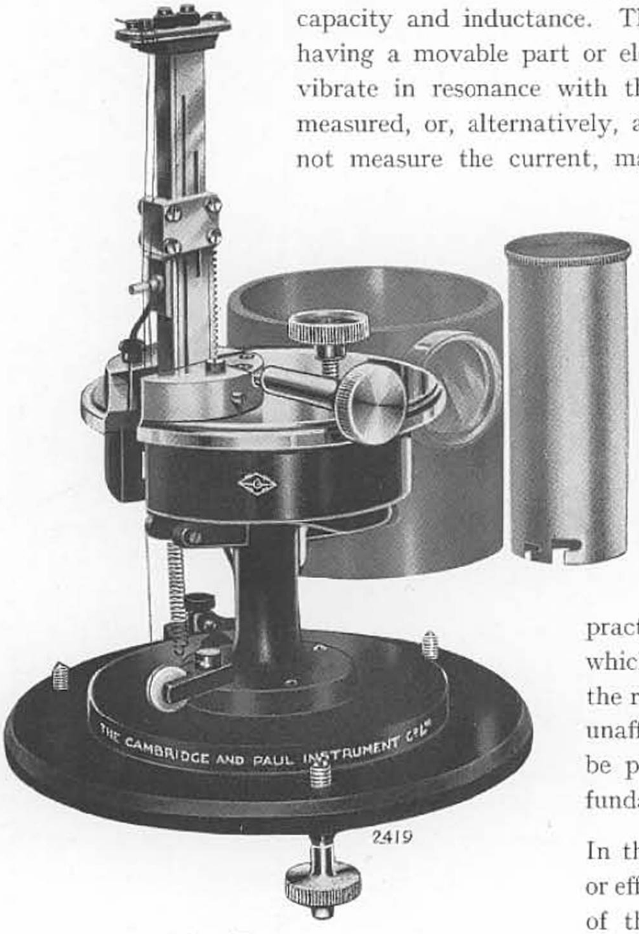

Fig. 27

20 × 20 × 33·8 cm. 5·6 kg.

When a vibration galvanometer is in tune with the frequency of the current, the resulting resonance vibration is usually much greater than the forced vibration which would be produced if resonance did not occur. This property possessed by vibration galvanometers of magnifying the resonance makes them highly sensitive measurers of alternating current. They are, moreover, relatively insensitive to currents of any other frequency, and this fact renders them highly selective, for they practically ignore all components of the current which have frequencies differing appreciably from the resonance frequency. They are almost entirely unaffected by any harmonic components which may be present, provided that they are tuned to the fundamental frequency of the current wave.

In the methods of measuring inductance, capacity, or effective resistance which are described in Part II. of this catalogue, a telephone is sometimes employed, but, unless the current is of pure sine form, a resonance instrument such as a vibration galvanometer is preferable. For frequencies up to 300 periods per second, a vibration galvanometer is more sensitive than a telephone; additional advantages are those of great robustness and freedom from injury from overload.

The Campbell Vibration Galvanometer, which is illustrated in Fig. 27, has a high sensitivity; it possesses low inductance and moderate effective resistance, and has, in addition, the advantage of being easily tuned.

The narrow moving coil, which has a low moment of inertia, is held in the narrow air gap of a permanent magnet by a double bifilar suspension. The effective length of the upper suspension can be varied by turning a pinion, which moves a rack; this rack is attached to a slide block, carrying a bridge-piece against which the suspension rests. The tension of the suspensions can be adjusted by a screw, which extends a spiral spring attached to the lower suspension. By these two adjustments the galvanometer can be brought into mechanical resonance with the supply frequency; the instrument

Campbell Vibration Galvanometer—*continued.*

is insensitive to harmonics, and this simplifies the measurements when currents which are not sinusoidal are employed.

The galvanometer is rigidly constructed, and is mounted on a heavy slate base to minimise the effect of external vibration. Ebonite blocks, fitted with rubber feet, are provided, on which the instrument should be supported.

The moving coils can be readily interchanged. The coil usually supplied can be tuned to any frequency from 40 to 1000 periods per second. The ohmic resistance of the coil is about 12, and of the suspension, 12 ohms. The coil is fitted with a plane mirror, and a 100-cm. focus convex lens on the case brings the spot to a focus on the scale. When using the instrument it is often convenient to set it up quite near to the scale, and to reflect the beam of light from an adjustable mirror placed opposite the observer at about half the usual scale distance. This mirror should be half as long as the scale used, in order to allow for the deflection of the beam.

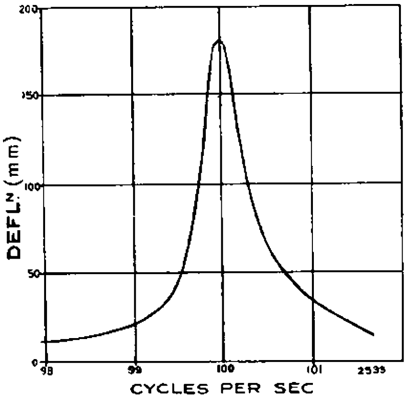

Fig. 28

For the lower frequencies, the sensitivity is inversely proportional to the frequency. Approximate data regarding sensitivity and effective resistance at various frequencies are given in Table No. VII.

It will be noticed that the sensitivity falls off quickly as the frequency increases.

TABLE No. VII.

Frequency ∿ per second ..	50	100	350	750	1000
Sensitivity (mm. at 1 m. per μA.)	60	20	3	0·5	0·2
Effective Resistance (Ohms)	500	350	160	52	35

The high sensitivity of these vibration galvanometers is obtained by reducing the damping to a small amount ; the resonance is therefore sharp, as will be seen from the typical resonance curve reproduced in Fig. 28. To employ the sensitivity to the full advantage, the frequency should be kept constant. If the frequency is inconstant, it is often better to flatten the resonance curve by adding a suitable shunt. When using null methods it is frequently advisable to begin with the galvanometer heavily shunted, and gradually to reduce the shunting to zero as the condition of balance is approached.

If the galvanometer is required for use on a low resistance bridge, a coil of a few turns and low effective resistance can be supplied.

Further information regarding vibration galvanometers will be found in papers by Campbell.[1]

Cat. No.
41521 **Campbell Vibration Galvanometer,** with coil for frequencies between 40 and 1000.

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[1] A. Campbell, *Phys. Soc. Proc.*, 1907, xx. 626, and 1919, xxxi. 85 ; also *Dictionary of Applied Physics*, 1922, ii. 960.

TUNED DETECTORS

Continued

Campbell Unifilar Vibration Galvanometer.[1]

This instrument, illustrated in Fig. 29, operates in the same manner as the bifilar type (described on pages 18 and 19), and the construction of the moving coil is the same. The range of tuning is from about 10 to 400 periods, and the galvanometer forms a convenient detector for use at these frequencies. The upper and lower suspensions are strips of phosphor-bronze. The tension on the suspensions can be easily adjusted, and the effective length of the upper suspension can be varied to bring the galvanometer into resonance with the frequency of the source of current. The galvanometer has the same insensitivity to harmonics as the bifilar type. The moving coils can be easily interchanged. A plane mirror is fitted to the coil, and a 100-cm. focus convex lens is fixed in the cover.

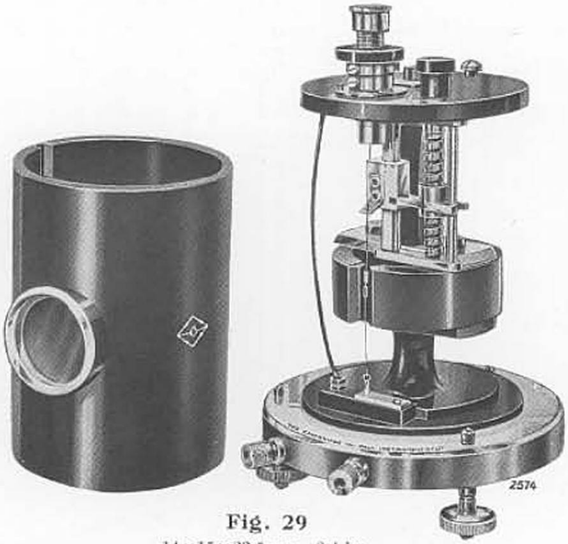

Fig. 29

14×15×23·5 cm. 2·4 kg.

Approximate sensitivity data are given in the following table :—

TABLE No. VIII.

Frequency ∽ per second	30	40	50	100	200
Sensitivity (mm. at 1 m. per μA.)..	20	20	25	40	10
Effective Resistance (Ohms)	30	40	50	120	70

A typical resonance curve for unifilar galvanometers is reproduced in Fig. 28.

Shunt Box for Vibration Galvanometers.

In order to obtain a high sensitivity in these galvanometers, the damping is reduced as much as possible. This reduces the speed of working so that it is usually convenient to shunt the galvanometer while getting an approximate balance in bridge measurements. For this purpose a shunt box can be supplied having positions for short and open circuit, and three shunts of 10, 100 and 500 ohms respectively.

Cat. No.
41524 **Campbell Unifilar Vibration Galvanometer,** with low resistance coil.
41526 **Shunt Box** for Vibration Galvanometers.

Tuned Telephones.

Telephone receivers, constructed for use as detectors in null methods, are adjusted so that the diaphragm resonates to the frequency of the source of current. By this means a greatly increased sensitivity is obtained. Single or double head-gear receivers are constructed, the head-band being insulated from the telephone receiver. The normal frequencies for which these detectors are made are 800 and 1000 per second, but they are constructed to order for frequencies even as low as 200. For use with an inductance bridge of medium resistance, a receiver having an internal resistance of about 150 ohms is suitable, no gain in sensitivity being obtained by the use of a higher resistance. For high resistance bridges, and for use as receivers in radio-telegraphic transmission, the high resistance telephones are more suitable.

TABLE No. IX.
Single and Double Tuned Telephone Receivers.

Cat. Nos.		Resistance (Ohms).
Frequency 800.	Frequency 1000.	
47411	**47415**	150
47412	**47416**	500
47413	**47417**	1000
47414	**47418**	1500
47421	**47425**	150+150
47422	**47426**	500+500
47423	**47427**	1000+1000
47424	**47428**	1500+1500

[1] A. Campbell, *Phys. Soc. Proc.*, 1913, xxv. 203.

GALVANOMETERS

FOR HIGH FREQUENCY MEASUREMENTS

THE instruments described in the following pages have been designed to measure small alternating currents of high frequency without introducing into the circuit any appreciable disturbance due to capacity or inductance. Though the instruments vary somewhat in construction, the principle employed is identical. The alternating current passes through a heater, near to which is placed one or more fine thermo-junctions, and the rise in temperature due to the current is indicated on a moving-coil galvanometer having a high volt sensitivity. The deflections of the galvanometer are practically proportional to the square of the current through the heater. The galvanometer is usually furnished with a proportional scale, the calibration being effected, on setting up the instrument, by passing a measured direct current through the heater. The heater consists of a short fine wire, or strip, of refractory material, of section proportioned to the current to be measured, and of small capacity and inductance. The heater and thermo-junctions are often supplied as an external accessory to the galvanometer, but portable instruments are also constructed in which the thermal accessory is enclosed in the galvanometer case. Portable instruments are described on pages 23, 28 and 29.

In one form of external thermal accessory, called an " independent junction," the junctions lie close to, but do not touch the heater. This form does not introduce any error due to capacity currents; the heaters are readily interchanged, and there are no reversal errors with continuous current. The independent junction is described on page 24. In another form, known as a " vacuo-junction," the thermo-junction is soldered to the centre of the heater, the whole arrangement being enclosed in an exhausted bulb; it has a somewhat higher watt sensitivity than that of the independent junction. Vacuo-junctions are described on pages 24 and 25.

In the simplest form, the heater and the thermo-junction are formed by looping together at their centres, two fine wires of iron and constantan respectively to form a " cross." This form of accessory is only suitable for rough measurements or for including in wavemeter circuits to indicate sharpness of tuning. Used in conjunction with a unipivot millivoltmeter, pattern " I," it is known as a High Frequency Galvanometer (see page 25).

The type of galvanometer used in conjunction with a thermal accessory depends on the sensitivity required in the combination, the rapidity desired in the readings and the necessity or otherwise for portability. Galvanometers of various sensitivities are described on pages 26 and 27, and their approximate constants, when used with standard independent junctions or vacuo-junctions, can be calculated from Tables Nos. X., XI. and XV.

The Duddell Thermo-Galvanometer and the Duddell Thermo-Ammeter, described on pages 22 and 23, are thermal instruments of a special form. The sensitivity data given in Tables Nos. XVI. and XVII. will enable customers to compare these instruments with the other combinations.

GALVANOMETERS

FOR HIGH FREQUENCY MEASUREMENTS—*continued*

Duddell Thermo-Galvanometer.

Although this instrument was constructed by the late Mr. W. Duddell, in 1889, as a development from Boys' radio-micrometer,[1] it still provides one of the most sensitive means of measuring small alternating currents; it has practically no self inductance or capacity, and can therefore be used on a circuit of any frequency, while currents as low as twenty microamperes may be readily measured. It can be accurately standardised by continuous current, and it can be used on circuits of any wave form; it has a short period, and is very dead beat.

The instrument, illustrated in Fig. 30, consists of a resistance which is warmed by the current to be measured, some of the heat thus generated heating the thermo-junction of a Boys' radio-micrometer. Referring to the diagram (Fig. 31), a single loop of wire L is suspended, by a quartz fibre Q, between the pole pieces N S of a permanent magnet. The loop is surmounted by a glass stem G carrying a mirror M, whilst its lower ends are connected to a bismuth-antimony thermo-couple (*Bi Sb*). The heater resistance is fixed immediately below the thermo-couple, and as it is a straight filament only 3 or 4 mm. long, with two straight wires leading to the terminals, the inductance and capacity are very small. The suspension, heater, etc., are protected from sudden changes in temperature by being enclosed in a heavy metal block with a removable front, shown on the left of Fig. 30. The heaters are set up in protecting cases with contact rings, so that they can be interchanged quickly when it is desired to alter the sensitivity of the instrument appreciably. The sensitivity may also be varied by altering the distance between the couple and the heater by turning an ebonite milled head. The clip which holds the heater has a spherical seating, so that it can be adjusted centrally under the thermo-couple by set screws. The suspension can be securely clamped. A large double cover, seen on the right in Fig. 30, thoroughly protects the instrument from outside temperature effects.

Fig. 30
22 x 22 x 35 cm. 10·3 kg.

The instrument is usually fitted with a plane mirror and convex lens of 1 metre focal length (for 1 metre scale distance). The period is normally between 3 and 4 seconds. The instrument is adjusted to be just aperiodic. It is very quick-acting; the spot swings up to its position and almost immediately comes to rest.

The resistance can be easily varied by substituting different heaters. Two heaters, of resistance about 4 and 100 ohms respectively, are usually supplied with each instrument, but heaters having resistances about 10, 40, 400 or 1000 ohms can be provided if desired; other resistances can be made to order. The heaters from 40 ohms downwards are metal wires, and are adjusted to within about ± 10 per cent. Those above 40 ohms consist of a deposit of platinum on quartz, and are adjusted to within about ± 5 per cent. of the above values. The deflections are practically proportional to the square of the R.M.S. values of the current when the heater is central under the junction.

Approximate sensitivity data of Duddell galvanometers with different heaters are given on page 30.

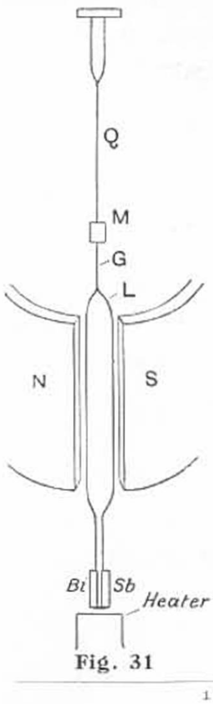

Fig. 31

Cat. No.
41611 **Duddell Thermo-Galvanometer** with 4 and 100 ohm heaters.
41612 **Ditto,** but without heaters.

[1] C. V. Boys, *Phil. Trans. Roy. Soc.*, 1889, clxxx. 159.
W. Duddell, *Phys. Soc. Proc.*, 1904, xix. 233; and *Phil. Mag.*, 1904, viii. 91.

Duddell Thermo-Ammeter.

This instrument may be regarded as a modification of the Duddell thermo-galvanometer, in order to produce a corresponding pivoted instrument.

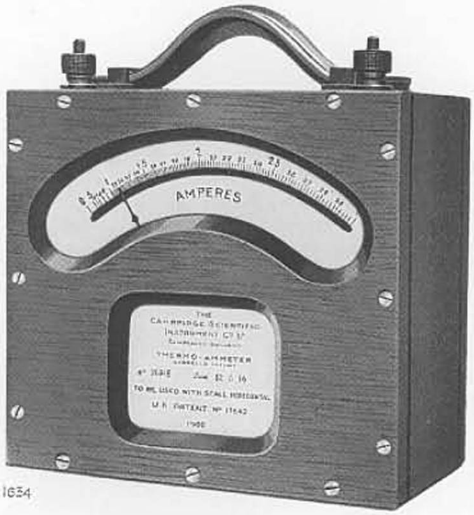

Fig. 32
21 × 11 × 22 cm. 3·2 kg.

The general appearance of the instrument is shown in Fig. 32, while Fig. 33 is a sectional diagram showing the arrangement of the heater and coil. It will be seen that the instrument is of the moving coil type, but instead of the coil winding *D* being brought out to terminals in the usual way, it is closed at the lower end by a thermo-junction *LM*, the elements of which are made from special alloys having a very high thermo-electric force. At its lower ends the thermo-junction is soldered to a thin circular "receiving plate" *J*, and immediately below this plate is fixed a stationary heater *K*, which is traversed by the current to be measured.

For currents above 20 milliamperes the heater is of wire, but for smaller currents platinised mica is used, the platinum being scraped away in parts to form a kind of grid. By this means a resistance of several hundred ohms may be easily obtained in a space of less than 0·2 sq. cm. When the current to be measured passes through this resistance, heat is transmitted to the receiving plate above and thence to the thermo-couple connected thereto. A thermo-electric current then flows round the coil, which consequently turns in the magnetic field, the deflection being indicated by a pointer in the usual way.

The moving coil is pivoted above and below, but the pivots are inside the coil, so that when the instrument is in use the coil is practically suspended from the top pivot, the lower pivot being almost entirely out of action. By this means pivot friction is reduced to a minimum.

No current passes through the control spring *F*, and the material of this spring may be selected without reference to its electrical resistance. One end of the control spring is attached to the lever *G*, which is connected to the pointer adjusting screw outside the case.

The maximum power taken is small, being about 0·015 watt, and the instrument will stand an overload of about three times its maximum working current. The standard heaters are of about 150 ohms and 1·5 ohms resistance respectively; the former is suitable for telephone work, and the latter for certain measurements in wireless telegraphy. The thermo-ammeter may be used with noninductive shunts. When the instrument is required for use on circuits of very high frequency, the use of shunts is not permissible unless the frequency is known and the corresponding change in the value of the shunt has been found.

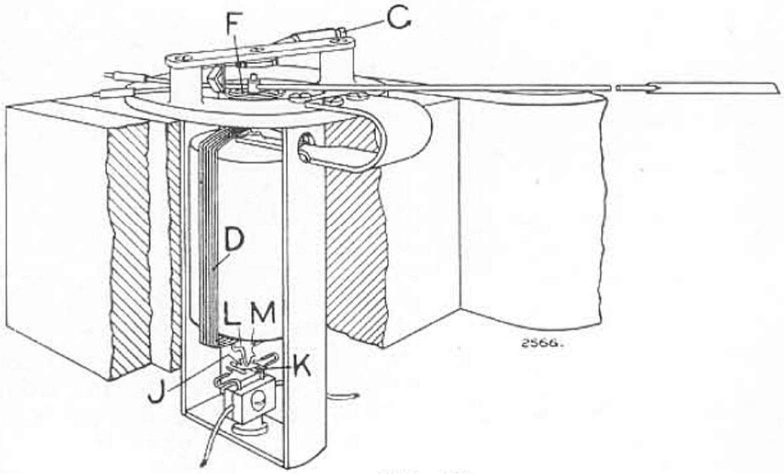

Fig. 33

Approximate sensitivity data of the thermo-ammeter with different heaters are given on page 30.

A specimen scale is reproduced full-size on page 38.

Cat. No.
41631 **Duddell Thermo-Ammeter,** resistance about 150 ohms, maximum deflection for 10 milliamperes.
41633 **Ditto,** resistance about 1·5 ohms, range 10–100 milliamperes.

GALVANOMETERS

FOR HIGH FREQUENCY MEASUREMENTS—*continued*

Independent Junctions.

The independent junction is particularly useful for the measurement of currents in short-wave wireless telegraphy, as its design eliminates the possibility of errors occurring due to capacity currents. It should be used when large high frequency currents are to be measured by taking the voltage drop on a shunt. In the latest model, illustrated in Fig. 34, the design has been simplified and the adjustments improved.

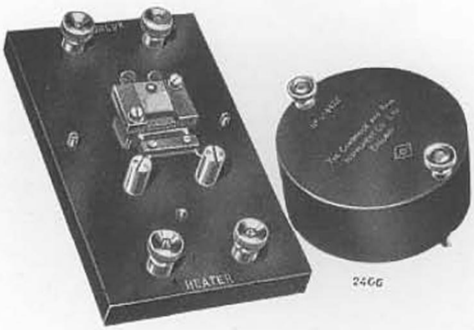

Fig. 34

8×13×6 cm. 4 kg.

A number of thermo-couples, connected in series with a galvanometer, are mounted with their hot junctions near to a heater, this heater having no electrical connection with the couples. When a current passes through the heater, an electromotive force is set up in the couple circuit, and the amount of current passing in the circuit is measured by the galvanometer; 10 thermo-couples are usually employed.

The position of the heater relative to the couples may be adjusted by slackening two clamping screws and then resetting the heater; as a fine adjustment, the frame bearing the couples can be rocked through a limited angle. The distance between the couples and the heater can be up to 3 or 4 millimetres. A cover of ebonite, which can be removed in a few seconds, allows all the parts to be readily inspected.

The heaters are readily interchanged. Table No. X. gives the approximate currents through the standard heaters which are required to produce full scale deflection of a unipivot galvanometer (range 2·4 millivolts, resistance 10 ohms); this corresponds to an open circuit potential of 4 to 5 millivolts. Other heaters can be made up to suit any current.

TABLE No. X.

Maximum Resistance of the 10 Couples = 15 Ohms.

Cat. No.	Heater Resistance (Ohms).	Safe Current (Amperes).	Current for Full Scale Deflection (Amperes).
41681	20	0·1	0·037
41682	10	0·17	0·057
41683	3	0·28	0·13
41684	1	0·5	0·22
41685	0·4	1·0	0·35

Any of the galvanometers described on pages 26 and 27 can be used with an independent junction, the type of instrument depending on the sensitivity required. Approximate sensitivity data of different types of galvanometers with independent junctions having standard heaters can be calculated from Table No. XV., on page 30, in conjunction with Table No. X.

Vacuo-Junctions.

In a vacuo-junction the thermo-junction and the heater are contained in a highly exhausted glass bulb of about 25 mm. diameter (see Fig. 35). The heater is a fine wire of refractory material supported between platinum leading-in wires. The ends of the thermo-junction are similarly supported, the centre of the thermo-junction being set exactly on the heater where it is lightly soldered; it takes up the temperature of the wire almost instantaneously. The temperature attained at the maximum working current is about 200° C.; increasing the current 50 per cent. causes no damage. Vacuo-junctions remain constant for long periods, and do not readily deteriorate unless seriously overloaded. A vacuo-junction may be calibrated with direct current, using a reversing key and taking the mean of the two readings, which will be found to differ but slightly.

To enable vacuo-junctions to be easily connected in circuit, and to be interchanged or replaced as desired, an insulating collar is fitted, provided with four studs to which the leading-in wires are soldered; these studs are so arranged that when the junction is placed in the proper holder, correct connection and polarity are ensured.

GALVANOMETERS

FOR HIGH FREQUENCY MEASUREMENTS—*continued*

Vacuo-Junctions—*continued.*

Two types of holder are made—a four-terminal pattern and a two-terminal pattern. In the four-terminal pattern, shown in Fig. 35, the junction is pushed into a socket in an ebonite block, the studs making contact with springs attached to the terminals on the block, one pair connecting to the alternating current circuit, and the other pair to any galvanometer. A simple cover is provided to protect the vacuo-junction from radiation. For exact work, the vacuo-junction should be used in a case, its connections being soldered to the terminals; this more effectively protects the vacuo-junction from radiation, which might disturb the readings.

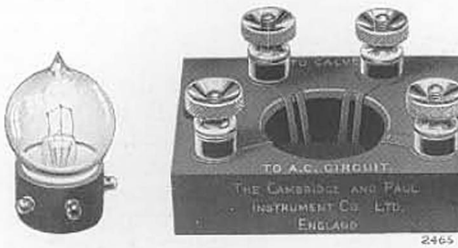

Fig. 35

6·6×5×5 cm. 0·1 kg.

In the other type of holder the bulb is held in an ebonite block fitted with two terminals, and with a device for direct attachment to unipivot millivoltmeter, pattern " I," in the same manner as the High Frequency Galvanometer attachment (Fig. 36).

A vacuo-junction, enclosed in a case, with resistances chosen to adjust the sensitivity to a standard value, so as to adapt the vacuo-junction for direct reading, is known as a thermal converter. These thermal converters are used with millivoltmeters having thermal scales; they are chiefly used with alternating currents of comparatively low frequency.

TABLE No. XI.
Vacuo-Junctions fitted with Contact Collar.

Cat. No.	Heater Resistance (Ohms).	Safe Current (Amperes).	Current for Full Scale Deflection (Amperes).
41671	30	0·015	0·008
41672	8	0·05	0·025
41673	1	0·25	0·12
41674	0·2	0·8	0·35
41675	0·12	1·6	0·7

Vacuo-junctions of various sensitivities are supplied for use with any suitable galvanometer. Table No. XI. gives the approximate currents through the heater which are required to produce full scale deflection of a unipivot galvanometer (range 2·4 millivolts, resistance 10 ohms); this corresponds to an open circuit potential of 4 to 5 millivolts.

Cat. No.
41691 **Four-terminal Holder.**
41692 **Ditto,** but with simple cover.
41693 **Case,** with ebonite top and terminals for soldered internal connections.
41694 **Two-terminal Attachment.**

High Frequency Galvanometers.

A unipivot millivoltmeter, pattern " I," used in conjunction with a simple form of thermal accessory, consisting of a heater and thermo-junction formed by looping together at their centres two wires 0·05 mm. diameter, of iron and constantan respectively, to form a cross, is known as a High Frequency Galvanometer. This is illustrated in Fig. 36. The normal range is about one ampere. The accessory is protected by a cover, which also acts as an electrostatic shield; the shield is completed by the case of the unipivot being connected to the moving coil. This arrangement is suitable for rough measurements, or for indicating sharpness of tuning in wavemeter circuits, but is not capable of accurate calibration.

Fig. 36

17×11·5×7·5 cm. 1·5 kg.

Cat. No.
41652 **High Frequency Galvanometer.**

GALVANOMETERS

FOR HIGH FREQUENCY MEASUREMENTS—*continued*

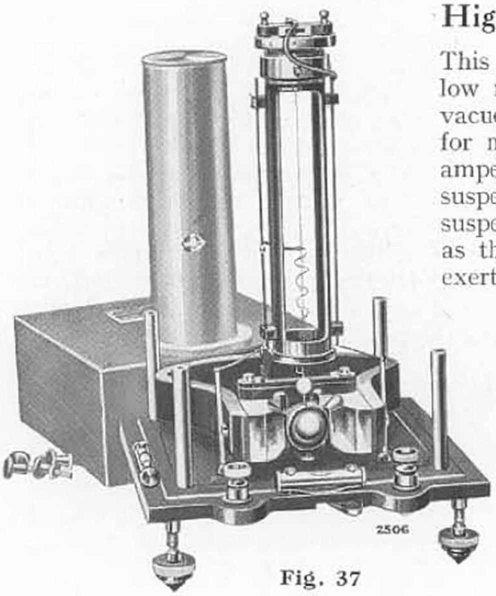

Fig. 37

21 × 19·5 × 34 cm. 5·4 kg.

High Sensitivity Reflecting Galvanometer.

This galvanometer, illustrated in Fig. 37, fitted with a coil of low resistance and used with an independent junction or a vacuo-junction, gives a high volt sensitivity such as is required for measuring high frequency currents down to a few micro-amperes. The coil moves in a radial magnetic field, and is suspended by a single flat strip of silver, the length of the suspension being about 22 cm. A spiral of the same material as the suspension forms the other connection to the coil, and exerts only a small controlling force. Care is taken that the coil shall move in a uniform magnetic field, and this, in conjunction with the long suspension, practically eliminates creeping of the zero. The magnetic circuit comprises a spherical core, accurately bored pole pieces, and a large well-aged permanent magnet; the pole pieces and cores are mounted on strong castings, which also support the torsion head. A coil-clamping device is fitted, which can be operated without opening the instrument case. Approximate sensitivity data of this galvanometer used with a vacuo-junction, Cat. No. 41671, are given in Table No. XV. A more complete description is given in our List No. 167, "Galvanometers."

Cat. No.
41811 **High Sensitivity Galvanometer.** Coil 15 ohms resistance, mirror 10 mm. diameter, period 22 seconds.

Cambridge A.M. Galvanometer.

In this moving coil galvanometer, the coil and magnet are of the form which has been found to have the greatest sensitivity for any given period.[1] The instrument, illustrated in Fig. 38, has been designed with a view to providing a simple and inexpensive galvanometer suitable for general laboratory work and for students' use. The coil, which moves in the narrow gap between the poles of a powerful permanent magnet of circular shape, is wound with carefully selected non-magnetic silk-covered wire on a wood former. The coil is suspended by phosphor-bronze strip from a simple torsion head held in position in the suspension tube by means of a spring; with this suspension, a stable zero is obtained. The instrument can be quickly and accurately levelled.

The galvanometer is fitted with a concave mirror of 8 millimetres diameter for a working distance of 1 metre, mounted on the coil former. When a bright spot of reflected light is required, as for lecture work, a mirror of approximately double the usual area can be supplied. For ordinary work, this large mirror has the disadvantage of extra weight.

Standard coils have the following approximate resistances:—30 ohms, 120 ohms, 250 ohms.
(Coils of other resistances can be supplied to order.)

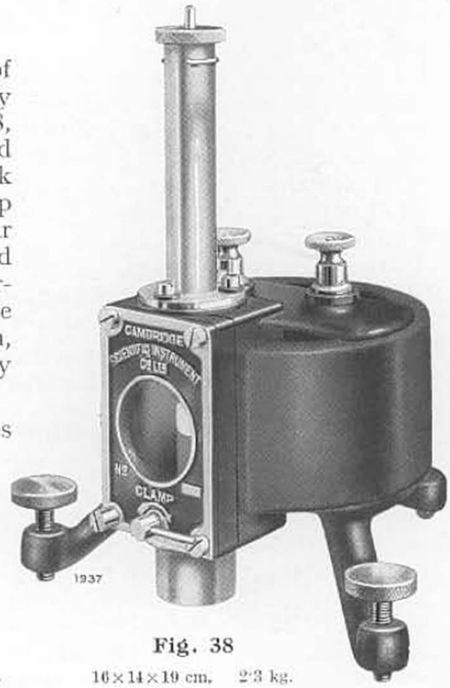

Fig. 38

16 × 14 × 19 cm. 2·3 kg.

Approximate sensitivity data of this galvanometer used with a vacuo-junction, Cat. No. 41671, are given in Table No. XV. The instrument is described in more detail in our List No. 167, "Galvanometers."

Cat. No.
41142 **Cambridge A.M. Galvanometer,** with coil, approximate resistance 30 ohms.
41143 **Ditto,** with coil, approximate resistance 120 ohms.
41144 **Ditto,** with coil, approximate resistance 250 ohms.

[1] Ayrton, Mather and Sumpner, *Phil. Mag.*, 1890, xxx. 58.

GALVANOMETERS

FOR HIGH FREQUENCY MEASUREMENTS—*continued*

Sensitive Pointer Galvanometer.

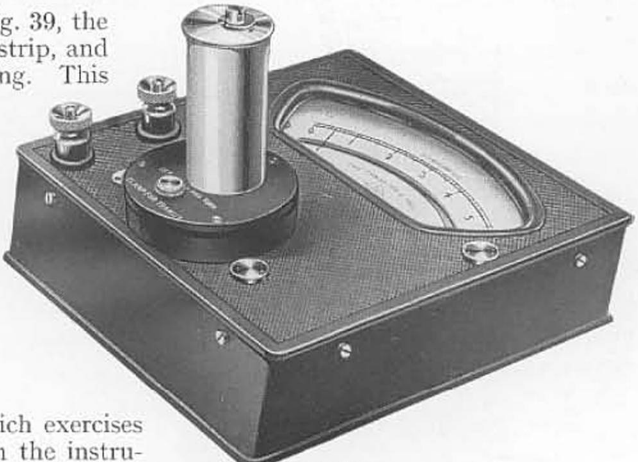

Fig. 39
17×16×15 cm. 2·2 kg.

In this pivoted galvanometer, illustrated in Fig. 39, the coil is suspended by a strong phosphor-bronze strip, and the upper end is attached to a thin flat spring. This spring is adjusted to support nearly the whole weight of the coil; pivot friction is therefore much reduced. There is no need for accurate levelling; the instrument may be five or ten degrees out of level without the working being affected. The instrument also has the advantage of being portable. Any shock to the instrument brings the pivot in contact with the spring jewel below it, and relieves the suspension of further strain; risk of breakage by ordinary usage is therefore eliminated. The other connection to the coil is made by a flexible silver spiral which exercises little control. Two scales can be provided on the instrument, one reading in millivolts and the other marked with a square-law scale numbered from 0 to 120. The length of the scale is approximately 110 mm. With a coil of about 10 ohms resistance, full scale deflection is given for 0·3 millivolt.

Approximate sensitivity data of this galvanometer used in conjunction with a vacuo-junction, Cat. No. 41671, are given in Table No. XV. A more complete description is given in our List No. 167, "Galvanometers."

Cat. No.
41821 **Sensitive Pointer Galvanometer,** with coil, resistance about 10 ohms.

Unipivot Galvanometer.

2095

Fig. 40
22×19×11 cm. 2·5 kg.

The unipivot is a sensitive moving coil instrument of robust construction, with the moving parts so disposed that accurate levelling is unnecessary. Various types of unipivots are made; one having a coil of about 10 ohms resistance and range 2·4 millivolts is best suited for use with a thermal accessory. Two scales are usually fitted, one reading in millivolts, and the other being a thermal scale numbered from 0 to 120. While the unipivot is more compact than the sensitive pointer galvanometer, and on account of its larger forces, its calibration is more permanent, its sensitivity is somewhat lower. Pattern "L" unipivot is illustrated in Fig. 40. The movement is mounted on the underside of a metal plate and fitted into a teak case, which can be provided with a detachable lid and carrying strap. The lid is fitted with a stud which depresses a clamping plunger, thus lifting the pivot from the jewel when the case is closed. The scale is approximately 110 mm. long. An actual scale is reproduced full-size on page 38.

Pattern "I" unipivot, shown in Fig. 36, is suitable for use in tropical climates. A coil-lifting device is provided; the length of the scale is approximately 75 millimetres.

Thermal attachments can also be used in conjunction with a unipivot, which is fitted with a system by means of which the transparent scale fitted to the instrument is projected on to a white screen with an enlargement of from 5 to 20 diameters. The enlarged image of the scale and pointer is brilliantly illuminated by a metal filament lamp or by a pointolite lamp, and is readable at a distance in broad daylight. Projection outfits are suitable for demonstration purposes.

Various types of unipivots are described in our List No. 160, "Unipivot Instruments for Direct Current."

GALVANOMETERS

FOR HIGH FREQUENCY MEASUREMENTS—*continued*

Portable High Frequency Galvanometer Outfits.

These outfits consist of a sensitive pointer galvanometer (see page 27) enclosed in a portable teak case, which also contains either a vacuo-junction or an independent junction. A constant is furnished with each outfit, by means of which the readings are easily converted into milliamperes. Approximate data are given in Table No. XII.

TABLE No. XII.

Cat. No. of Galvanometer with		Heater Resistance (Ohms).	Safe Current (Milliamps).	Range (Milliamps)
Vacuo-Junction.	Independent Junction.			
41825		30	15	4
	41826	20	100	14
		1	250	50
		0·4	1000	120

Fig. 41
22×19×11 cm. 2·6 kg.

Thermal Milliammeter, Single Range.

The instrument, illustrated in Fig. 41, consists of a type " L " unipivot having a vacuo-junction mounted inside the case ; the scale is calibrated throughout its length to read directly in milliamperes. A scale is reproduced full-size on page 38. The pointer comes to rest in about 5 or 6 seconds after switching on, and there is no appreciable zero error.

The instrument is fitted with a metal shield connected to the moving coils to eliminate electrostatic troubles, and small inductances are connected in the direct current circuit to protect the heater from capacity currents.

TABLE No. XIII.
Approximate Data of Single Range Thermal Milliammeters.

Cat. No.	Internal Resistance (Ohms).	Safe Current (Amperes).	Range (Amperes).
41337	30	0·015	0·008
	8	0·05	0·025
	1	0·25	0·12

These instruments are suitable for frequencies up to a million per second.

Instruments may also be ranged to currents 50 per cent. in excess of the values given in Table No. XIII.

Thermal Milliammeter, Multi-range.

High frequency alternating currents can be read directly on this instrument which give a continuous range of current measurement without breaking the circuit. It consists of 5 separate vacuo-junctions, each selected to give a convenient range of current measurement. The vacuo-junctions are mounted in a case with a sensitive unipivot millivoltmeter and a 6-way double-pole switch. Two terminals are fitted to the instrument, one of which is common to all the heaters. The positive elements of

Thermal Milliammeter, Multi-range—*continued.*

2552

Fig. 42

29×21·5×14 cm. 3·8 kg.

the thermo-junctions are connected together and to one end of the moving coil. The double-pole switch serves to connect, at the same time, the heater of one vacuo-junction to the right-hand terminal and the corresponding thermo-junction to the millivoltmeter. In passing from one connection to the next, the circuit remains unbroken. The switch positions are marked with the value of one scale division and the corresponding maximum reading; a sixth position, next to the highest current range, is provided with an air junction as an indicator.

The scale of the instrument is numbered 0 to 100. The vacuo-junctions are selected and adjusted to give similar calibration curves.

TABLE No. XIV.

Switch Position.	Scale Factor.	Maximum Reading (Milliamperes).	Approximate Internal Resistance (Ohms).
E	0·1	10	30
D	0·5	50	4
C	1	100	1·2
B	5	500	0·24
A	10	1000	0·12
O short, with air junction, about 10 amperes.			—

Cat. No.
41623 **Thermal Milliammeter.**

Thermo-Galvanometer, Small Pattern.

This instrument, illustrated in Fig. 43, is based on the accepted principle of a Wheatstone Bridge arrangement of thermo-couples, the galvanometer being a small double-pivoted moving coil instrument. It is not intended for accurate measurements and cannot be checked with continuous current. It may, however, be calibrated with alternating currents of commercial frequencies.

It is made in one range only, to 100 milliamperes approximately, and is supplied with an evenly divided scale. An actual scale is reproduced full-size on page 38.

Cat. No.
41625 **Thermo-Galvanometer (Small Pattern).**

2541

Fig. 43

7·5×7·5×4 cm. 5 kg.

GALVANOMETERS

FOR HIGH FREQUENCY MEASUREMENTS—*continued*

Sensitivity Data.

The selection of a suitable galvanometer for use with independent junctions or vacuo-junctions will depend on the sensitivity required in the combination, and on the rapidity desired in the readings. The approximate sensitivity of the various galvanometers described on pages 26 and 27, when used with a junction, may be compared by reference to Table No. XV., which shows the approximate currents required for maximum and minimum deflection when the galvanometers are used with a vacuo-junction having heater of 30 ohms resistance (Cat. No. 41671, page 25).

TABLE No. XV.
Scale distance = 1 metre.

Galvanometer Pattern and Resistance.	Cat. No. for Galvanometer.	Current for 1° Angular Deflection (Microamps).	Current for 10 mm. Deflection (Microamps).	Current for Full Scale Deflection (Microamps).	Current for 500 mm. Deflection (Microamps).
Pattern "L" Unipivot, 10-ohm coil	**41331**	1000	—	8000	—
Sensitive Pointer Galvanometer, 10-ohm coil	**41821**	400	—	3200	—
Cambridge A-M Galvanometer, 30-ohm coil	**41142**	—	120	—	900
High Sensitivity Reflecting Galvanometer, 15-ohm coil	**41811**	—	80	—	600

The approximate sensitivity of any of these galvanometers used with a vacuo-junction or with an independent junction having heaters of standard resistance, can be determined by increasing the values of the current given in Table No. XV., in proportion to the values given in the third column of Table No. XI. (page 25) or Table No. X. (page 24).

Example.—Required to find the sensitivity of the Cambridge A-M Galvanometer with independent junction (Cat. No. 41683).

Current for full scale deflection for vacuo-junction (Cat. No. 41671) ... ... = 0·008 amp.
Ditto, for independent junction (Cat. No. 41683) ... = 0·13 amp.
From Table No. XV., current for full scale deflection of Cambridge A-M galvanometer with vacuo-junction (Cat. No. 41671) ... ... = 900 microamps.
Current for full scale deflection of Cambridge A-M galvanometer with independent junction (Cat. No. 41683) ... = $\left(900 \times \frac{0{\cdot}13}{0{\cdot}008}\right)$ microamps.
= 17,000 microamps. approx.

The most sensitive combination is a high sensitivity galvanometer, 15-ohm coil, 22-second period (Cat. No. 41811), fitted for 7·5-metre scale distance with a vacuo-junction (Cat. No. 41671). The approximate currents required for deflections of 1 millimetre, 10 millimetres and 500 millimetres are 10, 30 and 224 microamperes respectively. The deflections may be modified by the insertion of resistance in the galvanometer circuit. Precautions should be taken to avoid errors due to unknown thermo-E.M.F.'s in this circuit. In all cases, deflections are practically proportional to the square of the current through the heater; it is therefore a convenience to have the galvanometer fitted with a scale following a square law.

In Table No. XVI. will be found approximate sensitivity data of the Duddell thermo-galvanometer when used with standard resistances as detailed on page 22.

TABLE No. XVI.
Scale distance = 1 metre.

Approximate Resistance of Heater (Ohms).	Current to give 10 mm. Deflection (Microamps).	P.D. to give 10 mm. Deflection (Millivolts).
1000	20	20
100	60	6
10	200	2
4	300	1·2
1	600	0·6

TABLE No. XVII.

Resistance of Heater (Ohms).	Current for Full Scale Deflection (Milliamperes).	Full Scale Deflection (Volts).
150	10	1·5
1·5	100	0·15

In Table No. XVII. will be found the approximate sensitivity of the Duddell thermo-ammeter when used with heaters of resistance 150 ohms and 1·5 ohms respectively.

MOULLIN VOLTMETER

(PATENTED)

THE power absorbed by the ordinary type of low-reading alternating current voltmeter is so great that its inclusion in a circuit is generally sufficient to disturb considerably the conditions to be observed. The enhanced difficulties of measuring small voltages at high frequencies are known to every radio engineer: the impedance of the necessary windings of a dynamometer becomes prohibitive, and an electrostatic instrument, besides being extremely insensitive, possesses a capacity which is comparable with the capacities proper to the high frequency circuits. The Moullin Voltmeter,[1] which depends for its action on the rectifying properties of a triode valve, possesses the unique qualities of absorbing no power from the circuit, and of possessing a negligible capacity. Its readings are unaffected by frequency, and are as reliable at a million periods per second as they are at fifty periods per second. A thermionic valve possesses the property of rectification, and the rectified current so produced may be used to measure the applied electromotive force by means of a galvanometer. In a thermionic triode, rectification can be produced either by the curvature of the anode current/grid potential characteristic, or by the curvature of the grid current/grid potential characteristic. When no alternating electromotive force is applied, some permanent anode current, and probably some grid current, will be flowing. If a rectifier is used as a voltmeter, it is therefore essential that in whichever circuit the galvanometer is placed, the rectified current for a given applied voltage should not only be sufficiently large to be indicated on a reasonably sensitive galvanometer, but should be comparable with the current which is normally passing through the instrument. This condition may be satisfied by suitably choosing the anode potential so that the change of mean anode current for a given electromotive force applied to the rectifier bears a maximum ratio to the current produced by the anode battery. If curvature of the anode current/grid potential characteristic is to be employed, this condition occurs when no separate anode battery is used and the anode is connected direct to the positive side of the filament; on the other hand, if curvature of the grid current/grid potential characteristic is utilised, the most suitable anode potential is about 70 volts.

Fig. 44

15×18×10 cm. 2 kg.

Type A Voltmeter.

This instrument, illustrated in Fig. 44, employs the curvature of the anode current/grid potential characteristic; a separate anode battery is therefore not required. The thermionic valve, galvanometer (a sensitive unipivot instrument) and auxiliary apparatus are mounted in a case, and, to use the instrument, it is only necessary to connect a 6-volt battery to the terminals of the filament seen on the right of the illustration, and to apply the alternating electromotive force to be measured between two terminals on the upper part of the case.

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[1] E. B. Moullin, *Wireless World and Radio Review*, 1922, x. 1; also paper read by E. B. Moullin before Inst. Elect. Engs., Dec., 1922, entitled *A Direct-reading Thermionic Voltmeter and its Applications.*

MOULLIN VOLTMETER

(PATENTED)—*continued*

It will be noted from the diagram of connections in Fig. 45 that, in addition to heating the filament, the 6-volt battery provides a means of making the grid 1·6V negative, so as to reduce grid damping to a negligible amount. This method of fixing the grid potential allows it to be made 0·25V more negative than if a separate small cell had been used; it also obviates the risk of the calibration being upset by deterioration of such a cell. To ensure an indefinitely long life for the valve, and to reduce ageing to a negligible amount, only 3·6V is applied to the filament. The scale of the microammeter is directly marked in volts, the standard range being 0 to 1·5 volts; readings can be obtained to 0·02 volt over most of the range. A reproduction of an actual scale is shown on page 38.

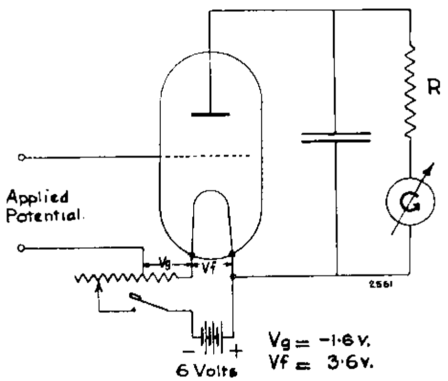


Fig. 45

The correctness of the calibration depends entirely on the filament battery, this being the only variable factor in the instrument; the exact conditions obtaining at the time of calibration are readily reproduced by adjusting the filament circuit rheostat which operates as a zero adjustment.

Having confirmed that there is a conducting circuit between the "volt-terminals" of the instrument—to ensure that the grid is at the correct potential—the valve is switched on, by depressing the key on the left, and the filament rheostat adjusted so as to bring the galvanometer to the zero of the volt scale (marked *O*), which, as will be seen from Fig. 44, does not coincide with the zero of the galvanometer (marked *A*). When this adjustment has been made, the anode current flowing is the same as at the time of calibration since this depends solely on the grid filament and anode potentials, all of which depend only on the filament current and the conditions obtaining when the instrument was calibrated are accurately reproduced. If the filament current were greater than at the time of calibration, the galvanometer pointer would be deflected further than the zero of the volt scale, and vice versa.

A conducting path must always exist between the "volt-terminals" of the instrument, or the grid potential will not be correct; for example, this voltmeter cannot be used to measure the potential drop across one of two condensers in series, for it is then converted into a cumulative grid rectifier, and the calibration is upset. The calibration is obviously upset if any steady potential exists between the "volt-terminals." In these cases, Type B Voltmeter must be employed.

By connecting the instrument across an inductance which forms part of a high frequency circuit, and then noting the amount the current in the circuit is changed by the introduction of the voltmeter, the effective resistance of the instrument at full scale deflection has been found to be at least 0·5 megohm. The power absorbed at full scale deflection is in consequence not more than 6 microwatts; the decrement introduced by the instrument is therefore so small as to be almost negligible.

The decrement δ introduced in an oscillatory circuit LC by a condenser leak of high resistance r is given by the equation

$$\delta = \frac{\pi}{r}\sqrt{\frac{L}{C}}$$

Suppose that $L = 2000\ \mu H$ and $C = 200$ micro-microfarads (corresponding to $\lambda = 1200$ metres), and that $r = 0{\cdot}75$ megohm, then

$$\delta = 0{\cdot}015.$$

Depending, as it does, on the medium of a valve, the readings of the voltmeter should be absolutely independent of frequency; exhaustive tests have proved this to be the case. The instrument has

MOULLIN VOLTMETER

(PATENTED)—*continued*

been used to measure the potential drop developed across a known resistance—due to the passage through the resistance of a constant current of variable frequency; it has been found that up to a frequency of one million cycles, the error at full scale deflection is certainly less than 2 per cent.

The voltmeter is mechanically robust and cannot be injured by an overload; it is as easy to use, and almost as portable, as an ordinary direct current instrument.

Type B Voltmeter.

As has already been pointed out (page 32), Type A Voltmeter cannot be employed either to measure an alternating potential superposed on a steady potential, or when the apparatus connected across its terminals does not form part of a closed conducting circuit; in these cases, Type B Voltmeter should be used.

The appearance of this instrument is shown in Fig. 46, while a diagram of connections is given in Fig. 47, where *G* is a sensitive milliammeter. The thermionic valve, milliammeter and accessories are enclosed in a case on which terminals are provided for connection to the anode and filament batteries; the alternating potential difference to be measured is applied between the terminals at the top of the case. The scale of the voltmeter is directly marked in volts, range 0–10 volts: 0·5 volt can be read with accuracy. An actual scale is reproduced full-size on page 38.

Fig. 46

15×18×10 cm. 2·1 kg.

The calibration of the instrument is inappreciably affected by small changes of anode or filament voltages, so that there is no need to reproduce accurately the conditions obtaining at the time of calibration. The permissible tolerances for both anode and filament potentials are marked on the instrument. Since the change of mean anode current consequent upon the application of a given e.m.f. to the grid is sensibly independent of small changes of anode potential, it is possible to compensate for these small changes by means of a zero adjustment on the pointer; with the valve switched on, and the anode battery connected, the pointer is brought to the zero of the voltage scale. Adjustment of the pointer in this way makes no sensible change in the voltage calibration. The effective resistance of Type B is probably even greater than that of Type A, and its calibration is equally independent of frequency; it cannot be damaged by overload. As it is unaffected by the existence of a steady potential difference between its terminals, it can be used to measure an alternating electromotive force superposed upon a steady electromotive force of large or small value.

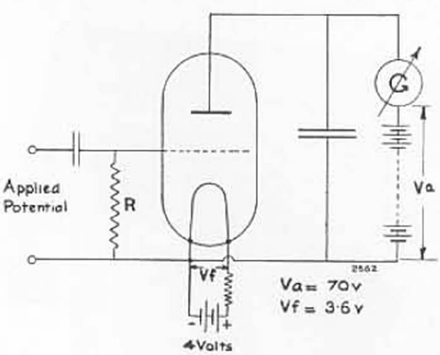


Fig. 47

A few typical examples of applications of both types of voltmeter at high frequencies are described in Part II. (page 48). In addition to being used for high frequency currents, both types have many applications at commercial frequencies.

Cat. No.	
42611	**Moullin Voltmeter, Type A,** range 0–1·5 volts.
42621	**Moullin Voltmeter, Type B,** range 0–10 volts.

CROSS-TALK METER

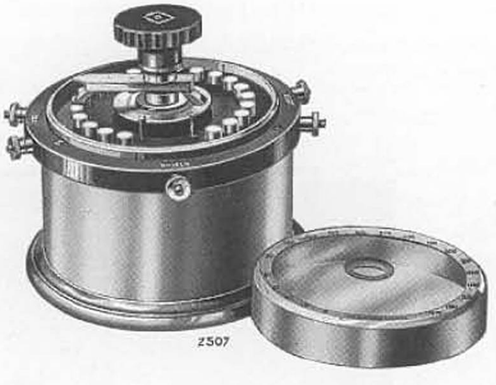


Fig. 48
17·5×17·5×15 cm. 3·6 kg.

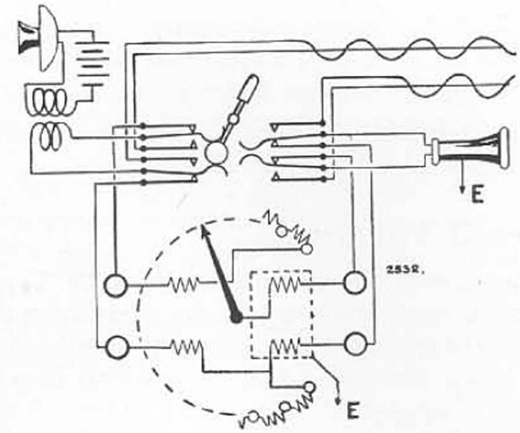


Fig. 49

THE object of this meter is to give a quantitative reading of the amount of cross-talk between two telephone circuits or apparatus. This measurement is becoming increasingly important, owing to the extensive adoption of loading coils and of superimposing.

The instrument consists of resistances, connected between contact studs, which are arranged as in the diagram (Fig. 49), and which are put into circuit by a circular switch of low resistance. In the illustration (Fig. 48) the meter is shown with cover removed, in order that the switch and contacts may be visible.

The diagram shows the meter connected up, with a reversing switch, transmitter, and receiver, for test on a cable pair. In the position of the reversing switch illustrated, the transmitter is connected to the cross-talk meter, the variable position of its shunt being connected to the receiver. On throwing over the switch, the transmitter is joined to one pair of cable wires, and the other pair is connected to the receiver. The test consists in adjusting the meter with the switch in the position illustrated, until the reception obtained is equal for both positions of the switch. The reading expresses the cross-talk in terms of an accepted unit, this unit being defined as the amount of cross-talk which causes a current in one circuit of one-millionth (10^{-6}) of the inducing current in the other circuit. The meters are wound and adjusted for a total of either 20,000 or 4,500 units. The impedance of the cross-talk meter is 666 ohms. The impedance of the receiver is 200 ohms at 800 cycles per second.

For accurate measurements, the connections to the switch should be carried in shielded conductors, in order to avoid any possibility of cross-talk in the apparatus, and the receiver should likewise be shielded. The receiver section coils of the meter are enclosed in a metal shield, which should be earthed. The reversing switch, transmitter, shielded receiver, and induction coil can be supplied separately in a portable case, as illustrated in Fig. 50.

Cat. No.

47431 **Cross-talk Meter,** in carrying case, 4,500 units.

47432 **Ditto,** 20,000 units.

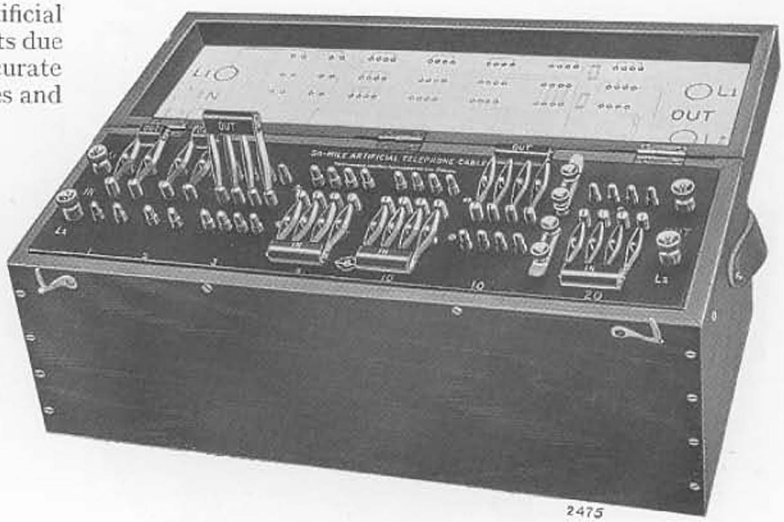
47439 **Portable Case,** containing switch, coil, and telephone.

Fig. 50 2468
18×18×12·5 cm. 1·4 kg.

STANDARD ARTIFICIAL TELEPHONE CABLE

Standard Artificial Telephone Cable.

This compact and portable artificial cable embodies many improvements due to Mr. B. S. Cohen. With it, accurate tests can be made of telephone lines and instruments, under working conditions, and in the laboratory. The telephone cable, illustrated in Fig. 51, is designed for rapid working, any length being instantly thrown in or out of circuit by means of switches which have been designed to prevent the development of contact errors after extended use.



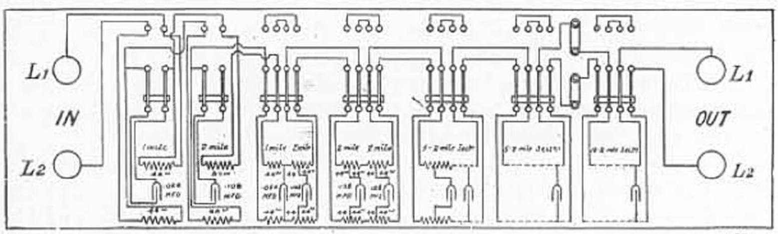
2475

Fig. 51

49 × 15·5 × 22·5 cm. 11·7 kilos.

Any length of standard cable can be put up in a portable teak case, and a diagram of the internal connections (as Fig. 52) is fixed in the lid. Fig. 51 shows a 50-mile cable (standard cable, 20 lb. per mile). Each mile consists of two resistances of 44 ohms each, representing the two lines, and a condenser of 0·054 microfarad, representing the capacity between the lines.

Multiples of two miles are divided into sections of two miles, each containing its separate condenser. In the improved construction, each sub-section (of which there are 26 in a 50-mile cable) is enclosed between two aluminium plates. All these plates are bolted to a metal frame, so that any section can be separately removed ; the plates act as shields to prevent mutual interference between the sections.



2255.

Fig. 52

Paraffined paper condensers, which have given so much trouble in connection with artificial telephone cables, have been replaced in this cable by mica condensers, and the whole construction is designed to enable the cable to stand a considerable amount of hard wear, and use in tropical climates.

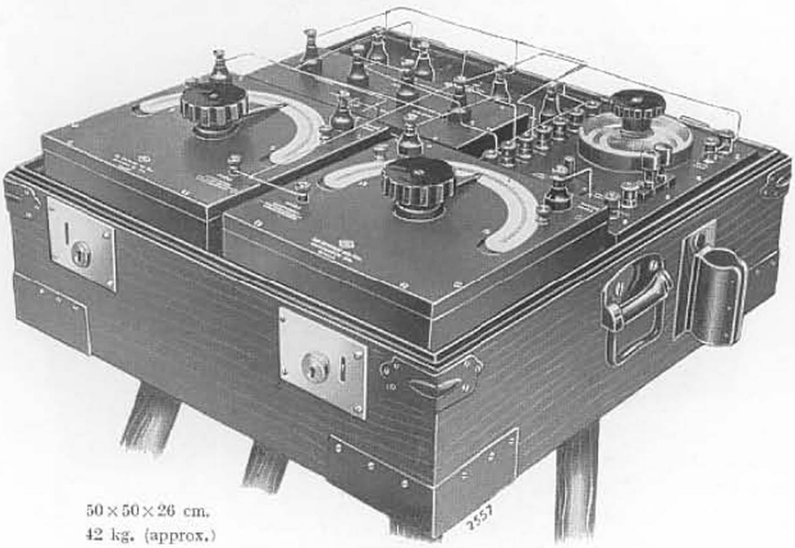
Artificial cables constructed in the same manner can also be supplied in fixed sections of 20 or 50 miles. No switches are fitted in these instruments, the section being brought out to four terminals.

Cat. No.	
47441	**Adjustable Artificial Cable.** Total 30 miles, sections 1, 2, 3, 4, 10, 10.
47442	**Ditto.** Total 50 miles, sections 1, 2, 3, 4, 10, 10, 20.
47443	**Ditto.** Total 60 miles, sections 1, 2, 3, 4, 10, 10, 10, 20.
47444	**Non-adjustable Artificial Cable.** One 20-mile section.
47445	**Ditto.** One 50-mile section.

TRUNK CABLE TEST SETS

Capacity Test Set.

Extended experience in the laying of multiple twin cables for underground telephone lines has made it possible to simplify the procedure for securing freedom from inductive disturbances or cross-talk. The wires of multiple twin cables are found to possess a sufficiently good balance with regard to self and mutual inductance for all requirements which have so far arisen, but, to avoid cross-talk, steps have to be taken to balance the electrostatic capacity of telephone circuits in these cables whenever the impedance of the circuits is increased by loading. With light gauge cables it is also sometimes necessary to balance the conductor resistance.



50 × 50 × 26 cm.
42 kg. (approx.)

Fig. 53

The apparatus described has been made to the design and specification of the British Post Office. The method employed is giving excellent results at moderate cost for testing, selecting and jointing, and admits of general application to multiple twin cables when these cables are required to provide loaded and superimposed circuits.

The tests are carried out by a portable equipment mounted on a table, as illustrated in Fig. 53, together with two boxes containing the generator, or reed hummer, and the batteries respectively. The reed hummer, which is described on page 17, supplies an alternating current at a frequency of approximately 1000 periods per second, the power being transmitted from the battery box to the reed hummer, and from the latter to a balanced and screened transformer. Measurements are made by means of an alternating current Wheatstone Bridge containing a pair of non-reactive ratio arms of 1000 + 1000 ohms, two fixed air condensers, and two continuously variable air condensers similar to those described on page 14. The bridge is first balanced when no cable is connected, and the out-of-balance capacity between either of two wires and a third is then measured by connecting the two wires to the outer corners of the bridge, the third wire being joined to the centre. The difference in the readings on the variable condenser gives the out-of-balance capacity. A switch, called a P.Q.R.S. switch, used in connection with a four-point plug, automatically connects each pair of wires to the outers, and the third wire to earth or to the middle point of the bridge. The screened transformer has been designed to have equal electrostatic capacities from the two halves of its secondary to the earthed screen between the primary and the secondary windings. The windings are also highly insulated, errors due to capacity to earth and leakage being thus eliminated. The capacity balance is such that when the bridge is balanced, the leads from the transformer secondary to the bridge may be reversed without causing appreciable error.

The maximum value of the condensers is approximately 0·0012 mfd., the scale being calibrated to read in micro-microfarads. Each division is 10 micro-microfarads and is subdivided into two parts each of 5 micro-microfarads. In the case of 176 yards of a 108 wire 100 lb. multiple twin cable, a division represents an error of approximately 0·66% in the wire-to-wire capacity, and an error of approximately 0·25% in the wire-to-earth capacity. It is possible with 1000 ohm ratio arms to read to 0·5 division when testing single lengths with the ordinary equipment; on longer lengths the sensitivity is still greater. For instance, on a two-and-a-half mile length of cable, the wire-to-wire capacity is approximately 0·0375 mfd., so that one division on the air condenser represents 1 part in 3750, while the wire-to-earth capacity is approximately 0·0942 mfd., so that one division on the air condenser represents 1 part in 9420. On this length of cable the sensitivity of the apparatus is sufficient to read easily to 0·5 division on the wire-to-wire condenser, and to 1 division on the wire-to-earth condenser.

Among the precautions to be taken when using the apparatus are the following :—

(*a*) Any moisture which condenses on the apparatus in damp weather should be wiped away with a clean rag and a little paraffin, and the apparatus should be stored overnight in a dry atmosphere to prevent moisture penetrating to the inside; high insulation of all parts is thus effected. Mounting the apparatus on paraffin wax is impractical and unnecessary.

TRUNK CABLE TEST SETS

Continued

Capacity Test Set—*continued.*

(*b*) The electrostatic screens of the balanced transformer, condensers and leads (if provided with screens) should be earthed by connecting them to the sheath of the cable under test by means of bare 100 lbs. copper wire or its equivalent.

(*c*) The connection of the testing leads to each core should be checked to ensure that the wires are fitted in the right order in the 4-point plug.

(*d*) Each section should be numbered in such a way as to enable the jointers to identify readily the joint referring to each jointing schedule.

(*e*) The accuracy of the jointing should be checked by means of the usual continuity tests.

50×50×24 cm.
40 kg. (approx.)

Fig. 54

Resistance Test Set.

A Resistance Test Set, which is illustrated in Fig. 54, has also been constructed for the British Post Office to its design and specification. This apparatus measures the out-of-balance resistance between two pairs of wires in a cable; it consists essentially of a Wheatstone Bridge, a switch-box and a galvanometer, all mounted in a portable case fitted with convenient handles. A diagram of connections is reproduced in Fig. 55. The Wheatstone Bridge has a total resistance of 11,111 ohms; it is provided with three pairs of ratio arms having resistance values of 10, 100 and 1000 ohms respectively, and is adjusted to an accuracy of one part in 10,000. The resistances *R* are arranged in decade units; the brushes are built up of laminated copper, and are continuous from end to end, each making independent contact between the central flange and the studs to which the coils are connected. The studs are faced with gold-silver alloy. To ensure smooth working, the brush spindle is fitted with a ball-bearing. Glass bezels, provided with bayonet catches, thoroughly protect the contacts from dust and dirt. The contacts are visible to the user and are easily accessible for cleaning and adjusting. To enable readings to be taken quickly, a switch is provided which has five positions:—"Loop Test," "Res. Out," "Slide Out," "Ratio Test," and "Off."

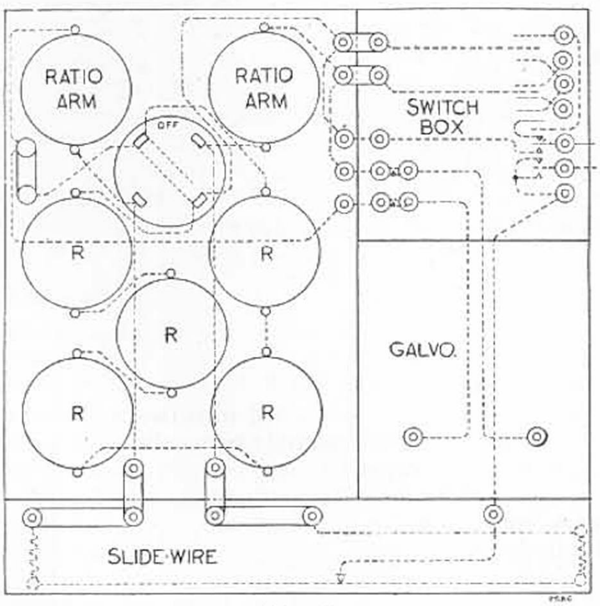


Fig. 55

A slide-wire enables the percentage out-of-balance resistance to be ascertained without calculation. The switch-box, which is external to the Wheatstone Bridge, facilitates connection being made to the wires composing the cable. A robust and sensitive unipivot galvanometer forms a convenient detector.

Cat. No.	
44348	**Trunk Cable Capacity Test Set.**
44349	**Trunk Cable Resistance Test Set.**

REPRODUCTIONS OF SOME ACTUAL SCALES

FULL SIZE

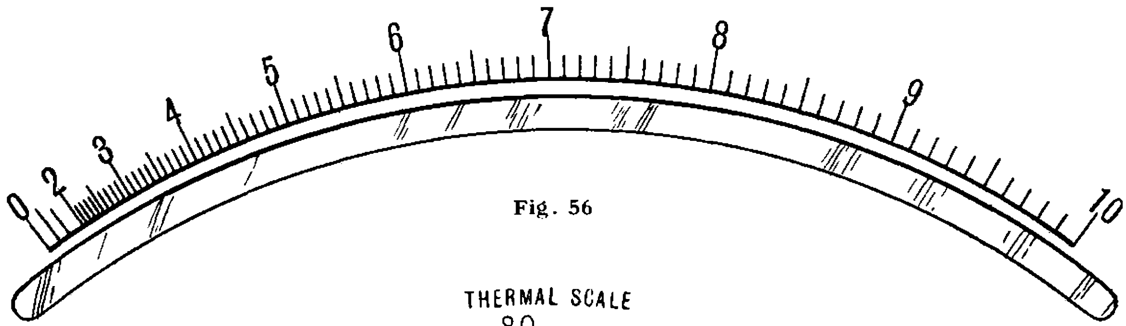


Fig. 56

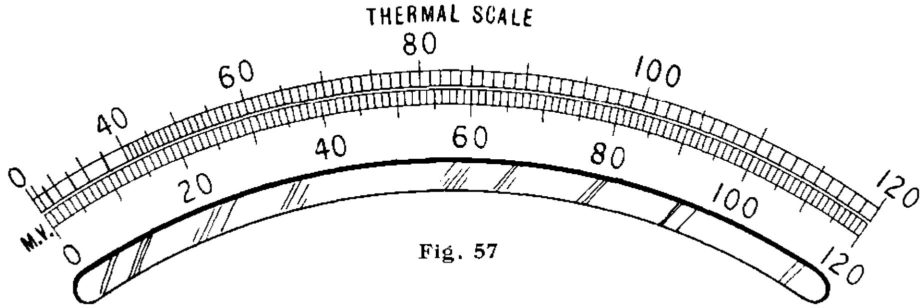


Fig. 57

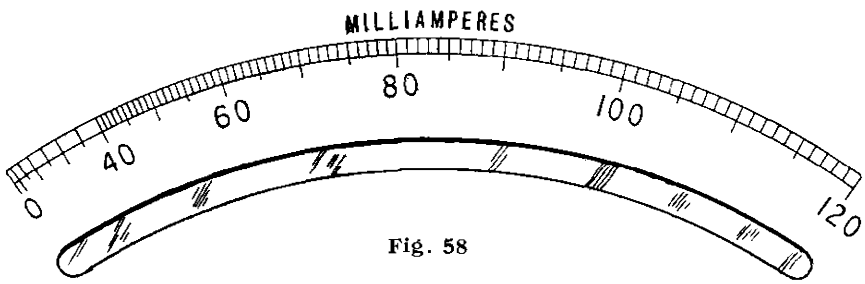


Fig. 58

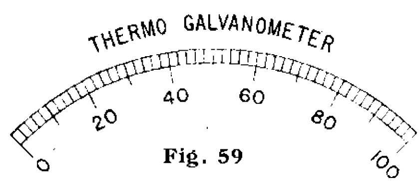


Fig. 59

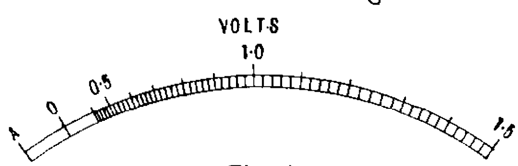


Fig. 60

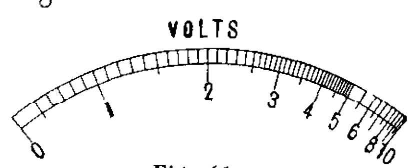


Fig. 61

PART II.

SOME METHODS OF MEASURING INDUCTANCE, CAPACITY AND RESISTANCE

General.

The various methods described in this section are those which have been found to be most generally useful, not only in the many commercial tests required by the electrical engineer, but also in connection with various branches of research work. The tests have been selected to meet general requirements, and have the advantage of being easily and quickly performed.

On pages 40 to 47, descriptions are given of a number of methods of measuring mutual and self inductance, effective resistance and capacity, while some applications of the Moullin Voltmeter are described on page 48; practical examples are given of most of the tests.

To obtain the most accurate results, the instruments described in Part I. of this catalogue should be employed; if desired, any of these instruments may be checked against the standard instruments at the National Physical Laboratory. The most useful apparatus, in addition to a suitable alternating current source and detector, will in general comprise: -standard mutual and self inductances (pages 4 to 6 and 8 to 9), precision mica and fixed plate condensers (pages 12 to 14), and standard resistances of low inductance (pages 10 and 11).

To obtain the best results, the bridge, or other arrangement of apparatus constituting the set up, should as far as possible comply with the following conditions :—

(*a*) All contacts and connections should be clean and tightly made.

(*b*) Open loops in the various arms should be avoided; to this end, all the junctions of a bridge should be near together.

(*c*) Care should be taken to see that no direct inductive action is taking place between the source and bridge or between the source and telephone; to test these effects, it is convenient to have reversing switches in the leads connecting the source and telephone respectively to the bridge.

(*d*) When testing inductive apparatus, it should be so disposed that no mutual inductance exists between it and other inductive parts of the bridge, such as the mutual standard; if this cannot be arranged, the leads to the inductive apparatus under test should be reversed, and a second set of readings taken.

(*e*) In general, and particularly with high impedance bridges, all the apparatus should be insulated on paraffin blocks.

Alternating Current Source.

It is generally advantageous to provide an earthed sheath or screen to intercept the capacity currents to earth from the direct current supply. In transformers, the screen may be conveniently a single layer of any wire between the primary and the secondary with its ends open-circuited and one of them earthed.

If a condenser is inserted between the source and the bridge to increase the current or to purify the wave form, it is advisable to insert half of the condenser in each of the leads to the bridge. Any precautions regarding screening are generally unnecessary if the Wagner Earthing Device (page 7) is used.

It is usually advisable to provide a number of secondary turns in the output circuit of the valve source, so that the power available for the particular method employed is most efficiently used; this procedure is adopted in the Valve Generator, Eccles Valve-maintained Tuning Fork and Reed Hummer (described on pages 15 to 17).

Detectors.

For frequencies up to 300 periods per second, a vibration galvanometer is usually more sensitive than a telephone (see page 18). The galvanometer should be mounted on a platform supported on three rubber toes, and the leads should be highly insulated.

If a telephone is used, it may be necessary, in some cases, to clamp the telephone receiver in a rigid position, owing to the impossibility of rendering it immune from direct effects of the inductometer. When a balance has been obtained, the head and the telephone should be moved about; if on moving the telephone the balance is appreciably disturbed, it should be moved further away from the inductometer or inductive coil producing the effect.

Telephones of 150 ohms are suitable for most tests. In the Fleming-Wien Capacity Bridge (page 45), the impedance of all the arms is high, and it is advantageous to use a high resistance telephone. Telephones for bridge work may have the air-gap between the diaphragm and the magnet reduced as much as possible, as the currents at which they are used are extremely small. Ordinary telephone receivers have about three times the current sensitivity at their resonant frequency. If, therefore, tests are to be made under conditions where frequency is unimportant, and in which there is insufficient sensitivity, a gain in sensitivity may be obtained by adjusting the frequency to suit the telephone.

Measurement of Mutual Inductance.[1]

Method of Simple Opposition.

Any unknown mutual inductance of a value lying within the range of the Campbell Variable Mutual Standard can be measured at once by this method.

Apparatus required :—A.C. Source and Detector (pages 15 to 20), Campbell Variable Mutual Standard M (page 4). M_1 is the unknown mutual inductance.

Referring to Fig. 62, M_1 is connected to M so that their primary coils P_1 and P are in series with each other and an alternating source, while the secondaries S_1 and S, with their windings in opposition, are connected in series to a detector G, such as a vibration galvanometer or a telephone. M is then adjusted until a balance is obtained, the detector indicating that the secondary current is zero.

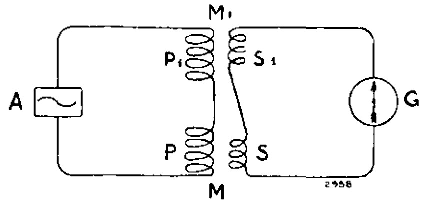


Fig. 62

$$\text{Then } M_1 = M.$$

If a vibration galvanometer is used, it is advisable to have a turning switch with a graduated series of shunts connected across the leads to the galvanometer, which should be kept shunted until an approximate balance has been obtained.

M_1 should be a considerable distance away from M, and if possible, it should be so placed as to have zero mutual inductance to it. Readings should be taken with reversal of leads going to P_1 and S_1 respectively. Readings should also be taken with the leads disconnected from the mutual and short circuited, in order to make correction for the small mutual between them. Sometimes a perfect balance cannot be obtained; this is usually due to capacity or to eddy currents in the windings of either or both mutuals. A perfect balance for the fundamental can always be found by connecting an adjustable condenser across one of the windings of either M_1 or M, as may be found by trial. This condenser will, however, produce a change in the effective mutual inductance. If L is the self inductance of the windings across which it is placed, the effective mutual inductance will be increased in the proportion of

$$1 : 1 + Lc\omega^2,$$

where c is the capacity of the condenser in farads and $\omega = 2\pi \times$ frequency.

If an alternating source is not available, direct current may be used, interrupted or reversed by a key, and a ballistic galvanometer then forms a suitable detector.

Maxwell's Method.

The measurement of mutual inductances larger than the Campbell Variable Mutual Standard cannot be made by the simple balancing method. In such cases the Maxwell Bridge Method[2] may be used.

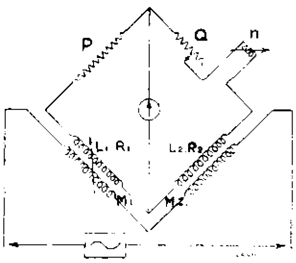


Fig. 63

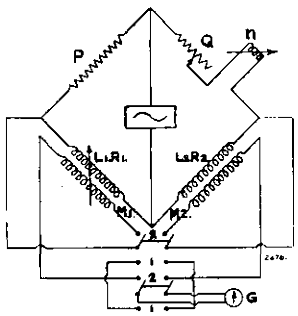


Fig. 64

Apparatus required :—A.C. Source and Detector (pages 15 to 20), Campbell Variable Mutual Standard M_1 (page 4), a fixed resistance P, a variable resistance Q, a variable self inductance n (page 9). M_2 is the unknown mutual inductance to be measured.

Connections are made as in Fig 63. If L_1 and L_2 are the inductances, and R_1 and R_2 the resistances of M_1 and M_2 respectively, the equations for balance are :—

$$\frac{M_2}{M_1} = \frac{L_2 - n}{L_1} = \frac{P + R_1}{Q + R_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The difficulty of having to make three adjustments, unless a separate bridge measurement has determined R_1 and R_2, can be overcome by an arrangement in which the equation connecting P, Q, R_1, R_2, L_1, L_2 and n is first independently satisfied. A throw-over switch is introduced to enable the simple bridge balance to be made first. The arrangement is shown in the diagram (Fig. 64). The switches are first placed in position 1, and a balance obtained by adjusting Q and n; the switches are then thrown over to position 2, and the final balance made by setting M_1 without altering L_1.

Example :—

Value of L_1 = 23 millihenries.
,, ,, L_2 = 110 ,,
,, ,, n = 0·5 ,,

Balance is first obtained with the switch in position 1; switch changed to position 2 and a balance obtained with M_1 at 9 millihenries.

$$\text{From (1)} \quad M_2 = \frac{(L_2 + n)M_1}{L_1}$$

$$= \frac{(110 + 0{\cdot}5)9}{23} \text{ millihenries}$$

$$= 43{\cdot}2 \text{ millihenries.}$$

[1] *Dictionary of Applied Physics*, 1922, ii. 392.
[2] Maxwell, *Electricity and Magnetism*, 2nd Ed., ii. 755.

Measurement of Self Inductance and Effective Resistance.

Heaviside Equal Ratio Bridge.

By this method, a wide range of self inductances can be measured with the help of a Campbell Variable Mutual Standard, self inductances from 0·1 to 2·2 millihenries being most accurately measured by using Standard Cat. No. 47211 (page 5), and self inductances from 1 to 22 millihenries by using Standard Cat. No. 47212 (page 5).

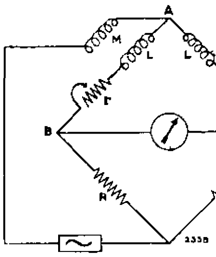


Fig. 65

It is, of course, understood that it is not necessary to use the low range Variable Mutual Standard for small self inductance measurements, but ten times the accuracy can be obtained when measuring coils up to the limit of 2·2 millihenries.

Apparatus required :—A.C. Source and Detector (pages 15 to 20), Campbell Variable Mutual Standard M (page 4), Low Induction Ratio Box RR (page 10), Low Induction Decade Resistance Box and Campbell Constant Inductance Rheostat r (pages 10 and 11).

N is the apparatus to be tested.

Connect as in Fig. 65, the point A representing the junction of the terminals F and a of the Variable Mutual Standard M (see Fig. 3, page 5), and LL being the two halves of the primary. Short-circuit N, and obtain a balance by adjusting r and M. Let the readings be r' and M'. Introduce N in the circuit, and balance afresh by readjusting r and M; call the readings r'' and M''. Then—

$$\text{Self inductance of } N = 2(M'' - M') \quad . \quad . \quad . \quad (2)$$

$$\text{Effective resistance of } N = r'' - r' \quad . \quad . \quad . \quad (3)$$

For the measurement of the residual inductances of resistance coils, a single scale standard is sufficient. In this case, and in other cases where high accuracy is required, corrections must be made for the residual inductances of r. These may be determined by using standard loop resistances of calculable inductances, by the method of replacement, or, if desired, a National Physical Laboratory certificate of the residual inductances of the Low Induction Decade Resistance Box can be supplied.

Precautions.—The coil under test should be removed a metre or so from the Standard, and should be connected up by lightly twisted leads. In highly accurate measurements, the capacity effect of the leads must be taken into account. If c is the capacity of the leads in farads, then—

$$\text{Effective inductance} = \text{true inductance } (1 + Lc\omega^2) \quad . \quad . \quad . \quad (4)$$

where L is in henries and $\omega = 2\pi \times$ frequency.

Readings should be taken with the leads to the coil reversed, and also with interchanged ratio arms.

Example :—

With N short-circuited, value of $M' = 1·5$ microhenries.
$r' = 1·9$ ohms.
With N in circuit, value of $M'' = 206$ microhenries.
$r'' = 80$ ohms.

From (2) Self inductance of $N = 2(M'' - M') = 2(206 - 1·5)$ microhenries
$= 409$ microhenries.

From (3) Effective resistance of $N = (r'' - r')$ ohms
$= 78·1$ ohms.

Self Inductance of Four-Terminal Resistances.

Four-terminal resistances require special circuits for the measurement of their self inductance. If the self inductance of a four-terminal resistance r is l, then l is related to the phase angle between the current and potential difference between the potential terminals by the expression—

$$\text{Sin } \theta = \frac{l\omega}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where r is the effective resistance between the potential terminals.

The following method, due to Campbell,[1] is satisfactory for resistances up to 1 ohm.

Apparatus required : A.C. Source and Detector (pages 15 to 20) ; a low reading mutual inductometer m, which can suitably be a single scale instrument, range to 1 microhenry ; mutual inductances M_1 and M_2 (these may consist of pairs of suitable mutual inductance coils, or two Campbell Variable Mutual Standards (page 4) may be employed) ; Low Induction Decade Resistance Box R (page 10). The primary circuit is linked to the detector circuit by an intermediary circuit of resistance R and self inductance L.

Connections are made as in Fig. 66.

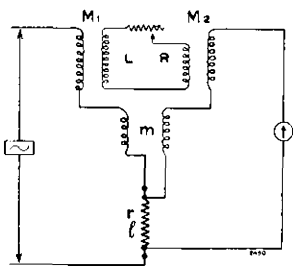


Fig. 66

The equations to be simultaneously satisfied for a balance are :—

$$m - l = \frac{Lr}{R}, \text{ giving } l \text{ in terms of the other known quantities.} \quad . \quad (6)$$

and $$Rr = [M_1M_2 - (m - l)L]\omega^2, \text{ where } \omega = 2\pi \times \text{frequency} \quad . \quad (7)$$

If m and M_1 or M_2 are made the two variables, the balance positions will be almost independent of each other, and no difficulty will be experienced in obtaining a balance ; otherwise m and ω may be varied, when the balance positions will be entirely independent of each other.

Example :—

$m = 50$ microhenries.
$L = 21800$ microhenries.
$r = 1$ ohm.
$R = 455$ ohms.

$$\therefore \text{ From (6) } \quad l = m - \frac{Lr}{R} = 50 - \frac{21800}{455} \text{ microhenries}$$
$$= 2·1 \text{ microhenries.}$$

[1] A. Campbell, *Phys. Soc. Proc.*, 1917. xxix. 345.

Carey Foster Bridge.[1]

This is one of the most adaptable and accurate methods of measuring the capacities and of deducing the energy losses or power factor of all kinds of condensers. The range of capacities is from a few micro-microfarads up to several microfarads, according to the values chosen for the various units of the bridge.

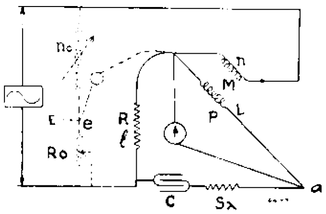


Fig. 67

The arrangement is as in Fig. 67. Connections for the Wagner Earthing Device (page 7) are shown dotted; this dotted part is not essential for the tests, but is advantageous for eliminating earth capacity effects when measuring small capacities.

Apparatus required :—A.C. Source and Detector (pages 15 to 20); Campbell Variable Mutual Standard M (page 4), the self inductance of the dials circuit of which is n; Carey Foster Auxiliary Box containing resistances R and P (page 7); Low Induction Decade Resistance Box S (page 10).

C is the capacity of the condenser to be tested.

The additional apparatus for the Wagner Earthing Device consists of a variable self inductance n_0 adjustable to be approximately equal to n, and a slide resistance R_0 adjustable to be approximately equal to R. These two latter items can be supplied to suit the standard being used (see page 7).

An approximate bridge balance is obtained by adjusting M and S, the galvanometer or telephone lead is then switched over from a to e, the earthed point. n_0 and R_0 are adjusted until an approximate subsidiary balance is obtained. The telephone lead is now replaced on a and the final bridge balance obtained by adjusting M and S. To a close approximation, the equations for balancing the bridge are :—

$$C = \frac{M}{PR}, \text{ where } C \text{ is in microfarads and } M \text{ is in microhenries} \quad (8)$$

and

$$S_0 = R\frac{(L - M)}{M} \quad (9)$$

where L is the self inductance of the secondary winding of the standard in the P branch (this is engraved on the instrument), and $S_0 = S$ (observed) $+ s$, where s is the resistance corresponding to the absorption loss in the condenser.

For accurate measurements, including the effect of the residual inductance of the arms, but excluding any impurity in the mutual inductance, the equations are :—

$$C = \frac{M}{PR}\left[1 + \left\{\frac{l\lambda - M(l + \lambda)}{PR}\right\}\omega^2\right] \quad (10)$$

where l, λ are the effective self inductances of the R and S branches respectively, and $\omega = 2\pi \times$ frequency;

and

$$S_0 = R\frac{(L - M)}{M} + \frac{Pl}{M} \quad (11)$$

A paper by S. Butterworth[2] gives a more complete treatment of the Carey Foster Bridge, including an investigation into impurity in the Variable Mutual Standard.

The power factor F is given by the equation :—

$$F = sC\omega, \text{ where } C \text{ is in farads} \quad (12)$$

To calculate S_0 it is necessary to know L. In some small condensers having large losses, s is greater than S_0, and no balance can be obtained. Additional known inductance should then be inserted in the P arm, taking care that it has no mutual inductance to the primary of the standard. The value of the resistance of this added inductance must, of course, be included in P when deducing capacity.

It is a help, when making tests on large condensers at telephonic frequency, to know the approximate value of the capacity; the values of M and S can then be set roughly so as to be near the true positions for balance. Otherwise, it is sometimes difficult to find the balance, as the two quantities M and S, which are varied, are not independent of each other in their effects on the balance.

Example :— P = 1000 ohms.
R = 10 ohms.

1.—*To find the capacity of the leads only.*
M is found to be 3 microhenries.

From (8) Capacity of leads $= \dfrac{3}{1000 \times 10} = 0{\cdot}0003$ microfarad.

2.—*To find C, the capacity of the condenser.*
M is found to be 1002 microhenries.

From (8) $C = \dfrac{M}{PR}$ − capacity of leads
$= \dfrac{1002}{1000 \times 10} - 0{\cdot}0003$
$= 0{\cdot}0999$ microfarad.

3.—*To find the power factor of a second condenser.*
P = 100 ohms.
R = 10 ohms.
L = 21·8 millihenries.
M = 1003 microhenries.
S = 206·7 ohms.
Frequency = 800 cycles.

$C = \dfrac{M}{PR} = 1{\cdot}003$ microfarads.

From (9) $S_0 = \dfrac{10(21{\cdot}8 - 1{\cdot}003)}{1{\cdot}003} = 207{\cdot}3$ ohms.

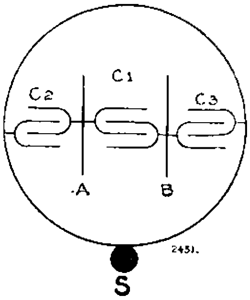
The resistance s corresponding to the loss $= S_0 - S$
$= 207{\cdot}3 - 206{\cdot}7 = 0{\cdot}6$ ohm.

From (12) The power factor $F = 0{\cdot}6 \times 1{\cdot}003 \times 10^{-6} \times 2\pi \times 800$
$= 0{\cdot}003$

[1] G. Carey Foster, *Phil. Mag.*, 1887, xxiii. 121.
[2] S. Butterworth, *Phys. Soc. Proc.*, 1920, xxxiii. 312.

Precautions when testing large condensers.—No special precautions are necessary when measuring the capacity of large condensers at low frequencies. At telephonic frequencies the frequency coefficient of the Standard must be taken into account (on the 11-millihenry instrument, Cat. No. 47212, this is of the order of one part in a thousand at a frequency of 1000 cycles per second, and varies as the square of the frequency). At frequencies of 2000 cycles per second (if accuracy to one part in a thousand is required), it may also be necessary to take account of the residuals in R and S. When making power factor measurements on large condensers (1 mfd.), it is generally necessary to include the correction term $\frac{Pl}{M}$; no other corrections are necessary in general, unless certainty to 1×10^{-4} in power factor is required.

Precautions when testing small condensers (variable and fixed air condensers, etc.).—To obtain sufficient sensitivity, these are usually tested at telephonic frequency. If the Wagner Earthing Device is not adopted, the point a of the bridge (Fig. 67) should be earthed; this will bring the telephone nearly to earth potential. In screened condensers, with the screen connected to one terminal, the resistance box S should be connected to this terminal, and in obtaining the zero balance for the leads, only the lead going to the unscreened terminal should be detached. Sometimes the condenser has its screen separately earthed; to measure the effective capacity, a three-reading method must then be adopted.



2451.

Fig. 68.

In Fig. 68, let A, B represent the two armatures of the condenser, and S the separate screen; also let C_1 be the inter-capacity between A and B and C_2, C_3 the inter-capacities between A, S and B, S respectively. The effective capacity C between A, B is then given by the equation :—

$$C = C_1 + \frac{C_2 C_3}{C_2 + C_3} \quad . \quad . \quad . \quad . \quad . \quad (13)$$

To determine C, the capacities C', C'' and C''' are measured, C' between AB (connected) and S, C'' between AS (connected) and B, and C''' between BS (connected) and A, giving :—

$$C' = C_2 + C_3 ; \quad C'' = C_3 + C_1 ; \quad C''' = C_1 + C_2 .$$

C is then given by the equation :—

$$C = \frac{C'' + C'''}{2} - \frac{C'}{4} - \frac{(C'' - C''')^2}{4C'} \quad . \quad . \quad . \quad (14)$$

(In most cases the third term is negligible.)

It is sometimes desirable to know the values of the earth capacities of each side of the condenser. These are given by

$$C_2 = \frac{C' + C''' - C''}{2} \text{ and } C_3 = \frac{C' + C'' - C'''}{2} \quad . \quad (15)$$

Example :—

C'	= capacity between A, B connected and	S	=	53	micro-microfarads.
C''	= ,, ,, A, S ,, ,,	B	=	503	,,
C'''	= ,, ,, B, S ,, ,,	A	=	500	,,

From (14) C, the deduced capacity between A and B, is given by

$$C = \frac{503 + 500}{2} - \frac{53}{4} \text{ (neglecting third term)}$$

$$= 488 \text{ micro-microfarads.}$$

From (15) $C_2 = \frac{C' + C''' - C''}{2} = \frac{53 + 500 - 503}{2} = 25$ micro-microfarads.

and $C_3 = \frac{C' + C'' - C'''}{2} = \frac{53 + 503 - 500}{2} = 28$ micro-microfarads.

Effective power factors may be deduced in the same way from exactly similar equations if S', S'' and S''', the effective shunt conductance of each of the three combinations of the condenser, are first deduced by measuring their series resistances. The expression giving the equivalent shunt resistance representing the loss in a condenser, when the series resistance s is measured, is approximately

$$S = \frac{1}{sC^2 w^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where $w = 2\pi \times$ frequency.

The above method of measurement is essential when deducing the constants of telephone cables by means of the Carey Foster Bridge.

Much valuable information regarding power factor measurements for condensers is contained in a paper recently published by Giebe.[1]

[1] E. Giebe and G. Zickner, *Verlustmessungen an Kondensatoren*, *Arc. für Elekt.*, 1922, xi. 109.

Carey Foster Bridge—*continued.*

Measurement of Large Self Inductances.

Large self inductances may be measured by inserting them in the P arm of the bridge. From the readings of M and S with and without the unknown coil, its effective self inductance and resistance can be calculated. It is convenient to have an adjustable low induction resistance box in the P arm, and to adjust this so as to keep M the same before and after adding the coil under measurement. If S_2, S_1 are the resistances required to balance the bridge with and without the unknown coil, the self inductance L' of this coil is given by the equation :—

$$L' = \frac{(S_2 - S_1)}{R} M \qquad (17)$$

Example :—

$S_2 = 2815$ ohms.
$S_1 = 1515$,,
$M = 166$ microhenries.
$R = 10$ ohms.

From (17) $L' = \frac{(S_2 - S_1)}{R} M = \frac{(2815 - 1515) \times 166}{10}$
$= 21580$ microhenries.

Measurement of Effective Inductance of Four-Terminal Resistance Coils.

If the conjugate Carey Foster Bridge is used (as in Fig. 69), the potential points of R carry no current, and, by using a condenser of known power factor, the term $\frac{Pl}{M}$ in the full formula (11) may be evaluated, giving l the effective self inductance of R. This method requires great accuracy in the measurements and a knowledge of L, the self inductance of the secondary winding of the inductometer.

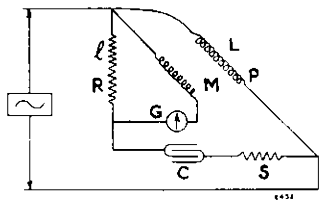


Fig. 69

Example :—

$M = 10020$ microhenries.
$L = 23060$,,
P arm $= 9860$ ohms (total).
$R = 0{\cdot}98$ ohm.
$S_0 = 3{\cdot}05$ ohms (total effective resistance of the condenser arm made up of resistance box value 2·5 ohms and condenser value 0·55 ohm).

From (11) $S_0 = \frac{R(L - M)}{M} + \frac{Pl}{M}$

$3{\cdot}05 = \frac{0{\cdot}98\,(23060 - 10020)}{10020} + \frac{9860\,l}{10020}$

whence $l = 1{\cdot}8$ microhenries.

Anderson's Bridge.[1]

This bridge compares capacity against self inductance and is independent of frequency.

Apparatus required :—A.C. Source and Detector (pages 15 to 20); Standard Condenser, having capacity C about 1 microfarad (page 12); Low Induction Variable Ratio with arms P, r (page 11); Low Induction Decade Resistance Box R, resistance 10,000 ohms (page 10); Low Induction Resistance Coil Q.

Connect up as in the diagram (Fig. 70). L and S are the self inductance and effective resistance respectively of the apparatus under test. Adjust R and r to obtain a balance, then

$L = 10^{-6}\,C(Rr + Sr + PS)$
$SP = QR$

or, if $P = Q$, then

$$L = 10^{-6}\,CR(2r + P) \qquad (18)$$
$$S = R \qquad (19)$$

where L is in henries and C is in microfarads.

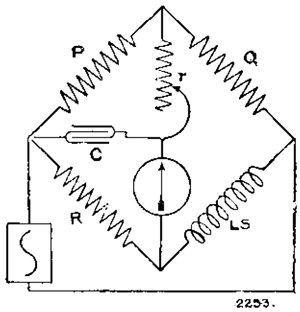


Fig. 70

Example :—

$P = 1000$ ohms.
$Q = 1000$,,
$C = 1{\cdot}003$ microfarads.
$R = 14$ ohms.
$r = 274{\cdot}5$ ohms.

From (18) $L = (10^{-6} \times 1{\cdot}003 \times 14)\,(2 \times 274{\cdot}5 + 1000)$
$= 21{\cdot}85$ millihenries.

Also from (19) $S = R = 14$ ohms.

Further information regarding the use of this bridge is given in a paper by Butterworth.[2]

[1] A. Anderson, *Phil. Mag.*, 1890, xxxi. 329.
[2] S. Butterworth, *Phys. Soc. Proc.*, 1921, xxxiv. 1.

Wien's Bridge.[1]

This bridge measures capacity and dielectric losses.

Apparatus required :—A.C. Source and Detector (pages 15 to 20), Low Induction Variable Ratio with arms S, Q (page 11), Low Induction Decade Resistance Box R (page 10), Standard Condenser C of high insulation resistance (page 12).

C_1 is the capacity and p is the equivalent insulation resistance of the condenser under test.

Connect up as in Fig. 71.

Obtain a balance by adjusting Q and S.

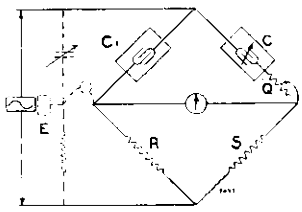


Fig. 71

Then
$$C_1 = \frac{S}{R}\,\frac{C}{1 + \omega^2C^2Q^2} \qquad (20)$$

and
$$p = \frac{R}{S}\,\frac{1 + \omega^2C^2Q^2}{\omega^2C^2Q} \qquad (21)$$

where $\omega = 2\pi \times$ frequency, and C_1 and C are in farads. If p is large, $\omega^2C^2Q^2$ is usually small enough to be neglected, and the first equation reduces to $C_1 = \frac{S}{R}C$.

Example :— $R = S = 1000$ ohms.
$C = 0{\cdot}0115$ microfarad.
$Q = 140$ ohms.
Frequency $= 1150$ cycles.

From (20) $C_1 = 0{\cdot}0115$ microfarad (neglecting $\omega^2C^2Q^2$).
$= 0{\cdot}0115 \times 10^{-6}$ farads.

From (21)
$$p = \frac{R}{S}\,\frac{1 + \omega^2C^2Q^2}{\omega^2C^2Q}$$
$$= \frac{1 + \{(2\pi \times 1150) \times (0{\cdot}0115 \times 10^{-6}) \times 140\}^2}{\{(2\pi \times 1150) \times (0{\cdot}0115 \times 10^{-6})\}^2 \times 140}$$
$= 1{\cdot}03$ megohms.

A modified form of this bridge, given by Giebe,[2] possesses some advantages over the Wien Bridge. The power factor adjustment is made by means of a variable air condenser shunting S instead of series resistance Q.

Capacity Ratio Arm Bridge.

A modification of Wien's Bridge, due to Fleming and Dyke,[3] has condenser ratio arms instead of the arms R and S. These may conveniently be standard fixed plate condensers (page 14). In many cases a more sensitive bridge is obtained, and the fixed condensers are more perfect electrically than the resistance arms because they have no appreciable voltage vector in quadrature with the main voltage vector on them.

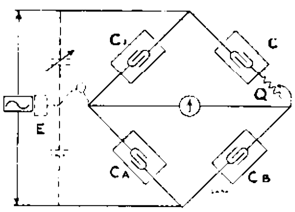


Fig. 72

For accurate work the condensers should be screened, and the screens should be connected up to the telephone terminals of the bridge. The resistance box Q should be inserted on the telephone side of the condenser (as in Fig. 72), and one end of it should be connected to the screen of condenser C.

For accurate measurements of power factor, it is practically essential to apply the Wagner Earthing Device shown dotted in the diagram.

If the tests are in the nature of measurement of dielectric loss, the condenser made up of the dielectric should, if possible, be self-screened, and when carrying out the tests only the insulated terminal should be disconnected when taking the zero balance. It is desirable to use a high resistance telephone, because all the arms of the bridge have high reactance.

Hughes-Rayleigh Bridge.[4]

This is a mutual inductance bridge depending upon frequency; by suitably choosing the values of the components, the bridge may be used for measuring low frequencies without necessitating large inductances.

Apparatus required :—A.C. Source and Detector (pages 15 to 20), Mutual Inductance M (this can either be a variable or a fixed inductance), Self Inductance n (page 9), Low Induction Variable Ratio with arms R, S (page 11), Fixed Resistance P, Low Induction Decade Resistance Box Q (page 10).

Connections are made as in Fig. 73.

The conditions for balance are :—
$$M(P + Q + R + S) = nR \qquad (22)$$
$$PS - QR = Mn\omega^2, \qquad (23)$$
where $\omega = 2\pi \times$ frequency.

Equation (22) is independent of frequency. If the galvanometer lead a is a potential slider on a slide wire connecting n and S, then by adjusting a equation (23) can be satisfied for any frequency within certain limits, whilst equation (22) is undisturbed. The slide-wire may be calibrated directly in terms of frequency.

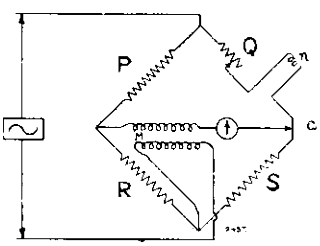


Fig. 73

Example :— $P = 1026$ ohms.
$Q = 1022$,,
$R = 100$,,
$S = 100$,,
$n = 0{\cdot}00136$ henry.

From (23)
$$M = \frac{nR}{P + Q + R + S}$$
$$M = \frac{0{\cdot}00136 \times 100}{1026 + 1022 + 100 + 100}\ \text{henries}$$
$$= \frac{0{\cdot}136}{2248}$$
$= 60{\cdot}5$ microhenries.

---

[1] M. Wien, *Wied. Ann.*, 1891, xliv. 689.
[2] E. Giebe and G. Zickner, *Arc. für Elekt.*, 1922, xi. 109.
[3] J. A. Fleming and G. B. Dyke, *J. Inst. El. Engs.*, 1912, xlix. 323; also *Phys. Soc. Proc.*, 1911, xxiii. 117.
[4] D. E. Hughes, *J. Inst. El. Engs.*, 1886, xv. 6; also Lord Rayleigh, *Phil. Mag.*, 1886, xxii. 469.

Campbell's Method of Measuring Large Capacities or Frequencies.[1]

Apparatus required :—A.C. Source and Detector (pages 15 to 20); Campbell Variable Mutual Standard M (page 4), the inductances of the primary P and the secondary Q being N and L respectively; Variable Condenser c, capacity 0·002 microfarad (page 14).
C is the capacity under test.

The diagram (Fig. 74) shows a method of balancing a mutual inductance against a condenser. The addition of condenser c is due to Mr. Butterworth.[2] Its object is to balance out the small residual sound in the telephone which is due to the losses in the main condenser and in the mutual inductance. The effect of these losses is to put in series in the condenser circuit an apparent small resistance S, which introduces an unbalanced vector into the telephone circuit. A perfect balance for the fundamental can be obtained by using condenser c.

If C is a high-class condenser, the residual sound in the telephone is small when no auxiliary condenser c is used. The position of minimum sound can be located to a few parts in ten thousand. Under these conditions the single equation to be satisfied is :—

$$MC\omega^2 = 1, \text{ where } \omega = 2\pi \times \text{frequency}, \qquad (24)$$

M is in henries and C in farads.

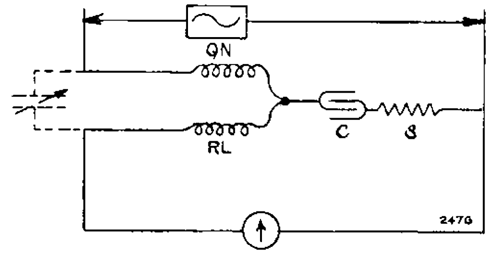


Fig. 74

Example :—

$M = 8{\cdot}05 \times 10^{-3}$ henries.
$C = 4{\cdot}99 \times 10^{-6}$ farads.

From (24) $\quad M c\omega^2 = 1$

$$\therefore (\text{Frequency})^2 = \frac{10^9}{8{\cdot}05 \times 4{\cdot}99 \times (2\pi)^2}$$

$\therefore$ Frequency $= 795$ cycles per second.

When c is used to obtain a more perfect balance, and when measuring the losses, represented by S, two equations have to be satisfied :—

$$MC\omega^2 = 1 - \frac{c}{M}\{QR - \omega^2 (L-M)(N-M)\} \qquad (25)$$

$$S = c\omega^2 \{R(N-M) + Q(L-M)\}. \qquad (26)$$

When adjustment is made by varying M and c, the balances are not independent of each other. This may make the perfect balance rather difficult to find; if a small adjustable resistance s is inserted in the condenser circuit, then by varying M and s the balances are almost entirely independent of each other.

When applied for measuring frequency, this method is quick; it is probably the most sensitive method known for measuring small changes of frequency. By using a variable air condenser in parallel with C, it is possible to measure with ease and certainty changes as small as one part in a million in frequency. If the frequency is known, the method can be used to measure either mutual inductance or capacity, if the other constant is known.

The device may also be used as a sifter for the purpose of eliminating any desired frequency from the circuit represented by the telephone. It forms a simple and sensitive method of ascertaining whether the wave form of a source is a sine wave. If a harmonic of only one-tenthousandth of the amplitude of the fundamental is present, it can be detected by this means.

Hay's Method of Measuring Large Self Inductances and Effective Resistance.[3]

Apparatus required :—A.C. Source and Detector (pages 15 to 20); a Standard Condenser C of high insulation resistance (page 12); Low Induction Variable Ratio with arms S, r (page 11); Low Induction Decade Resistance Box R (page 10). (N) is the apparatus under test of self inductance L. Connect up as in the diagram (Fig. 75).
Adjust R and r to obtain a balance, then

$$L = RS \frac{C}{1 + \omega^2 C^2 r^2} = RSC \text{ approximately}. \qquad (27)$$

where $\omega = 2\pi \times$ frequency.

$$\text{Effective resistance of } (N) = \frac{RS\omega^2 C^2 r}{1 + \omega^2 C^2 r^2}$$

$$= LC\omega^2 r \text{ approximately} \qquad (28)$$

where C is in farads and L is in henries.

These expressions involve the frequency; this is conveniently measured by the Campbell method.

Example :—

$R = 597$ ohms.
$S = 37$,,
$r = 32$,,
$C = 1 \times 10^{-6}$ farads.
$\omega = 5000$.

From (27) $\quad L = RSC = (597 \times 37 \times 10^{-6})$
$= 0{\cdot}0221$ henry.

From (28) Effective resistance of $(N) = LCr\omega^2$
$= 0{\cdot}0221 \times 10^{-6} \times 32 \times (5000)^2$
$= 17{\cdot}7$ ohms.

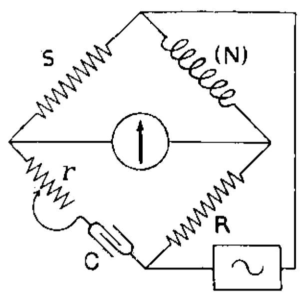


Fig. 75

[1] A. Campbell, *Proc. Phys. Soc.*, 1908, xxi. 69.
[2] S. Butterworth, *Phys. Soc. Proc.*, 1920, xxxiii. 337.
[3] C. E. Hay, *Inst. of Post Office Elec. Engs. Proc.*, Nov., 1912.

Tuned Arm Method of Measuring Effective Resistance.

Apparatus required :—A.C. Source and Detector (pages 15 to 20) ; Standard Condenser C of high insulation resistance (page 12) ; Variable Self Inductance n (page 9) ; Low Induction Ratio Box with arms R, S (page 11) ; Fixed Resistance Q ; Low Induction Decade Resistance Box P.

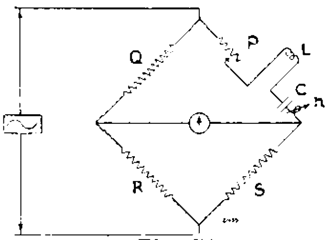


Fig. 76

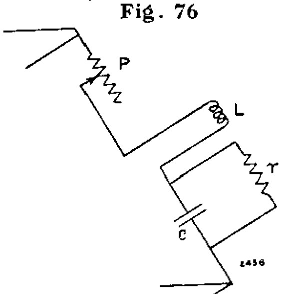


Fig. 77

L is the self inductance of the apparatus under test.

Connections are made as in Fig. 76. The self inductance L and the condenser C, which are in series in one arm of a Wheatstone Bridge, are made to resonate by varying the frequency or by putting in series a small variable self inductance. The method actually measures the sum of the effective resistances of L and C ; if either is known, the other can be determined.

A balance is first obtained with L and C both short-circuited. Let P_0 and n_0 be the readings corresponding to this balance ; L and C are now inserted, and a new balance obtained by adjusting P and n to the values P_1 and n_1.

Then the sum of the effective resistances of L and C is

$$P_0 - P_1 \qquad (29)$$

$$\text{and } (L + n_1 - n_0)\,C\omega^2 = 1 \qquad (30)$$

where $\omega = 2\pi \times$ frequency.

Example (to find the effective resistance of a paper condenser at 950 cycles) :—

P_0 = 184 ohms.
L = 14,700 microhenries.
P_1 = 169 ohms.
n_1 = 151 microhenries.
n_0 = 49 ,,
Effective resistance of L = 14·64 ohms.
∴ From (29) effective resistance of C = (184 – 169 – 14·64) ohms
= 0·36 ohm.

$$\text{Also from (30)} \qquad C\omega^2 = \frac{1}{L + n_1 - n_0} = \frac{1}{14802}$$

whence C = 1·9 microfarads.

If L is a high-class coil of the wavemeter type, its effective resistance may be measured at two or three radio-frequencies by suitable methods. By extrapolation down to the telephonic frequency, the effective resistance of the coil can be deduced accurately. By difference, it then becomes possible to ascertain the effective resistance of the condenser.

The method is susceptible of extreme accuracy and sensitivity, but it is somewhat inelastic in operation. It can, however, be successfully used to measure the effective resistance of large variable self inductances, such as those used for measurements of effective resistance and inductance of telephone loading coils and other inductances of the order of a hundred millihenries. When using the method for measuring the effective resistance of the condenser, a high-class standard inductance must be used, as mentioned above. If this is done, using two or three standard inductances, it is possible to determine the law of the variation of the resistance of the condenser with frequency to an accuracy which is probably greater than that of any other method.

More elasticity is given to the tuned arm method by shunting the condenser with a low induction resistance r, as in the diagram (Fig. 77), in which the rest of the bridge is the same as in Fig. 76. The equations for balance are :—

$$L = \frac{Cr^2}{1 + C^2r^2\omega^2}, \text{ where } \omega = 2\pi \times \text{frequency} \qquad (31)$$

$$\text{and } P = Q - \frac{r}{1 + C^2r^2\omega^2}. \qquad (32)$$

Maxwell's Commutator Bridge.[1]

This bridge measures capacity in terms of resistance and frequency.

Apparatus required :—Moving-Coil Galvanometer of resistance g ; Commutator ; Low Induction Variable Ratio with arms R, S (page 11) ; Fixed Resistance P.

C is the capacity of the condenser under test.

The connections are made as in the diagram (Fig. 78). The principle of the method consists in charging the condenser by connecting it to form one arm of a bridge, and then discharging it by short-circuiting after disconnection from the bridge. A revolving commutator performs these operations at any desired steady frequency. The galvanometer receives equal and opposite quantities of electricity every period when the balance is obtained. Since, however, it carries a relatively large alternating current, the galvanometer should be of long period and over-damped, otherwise a large-forced movement of the light spot will result. Neglecting battery resistance, the equation for balance is :—

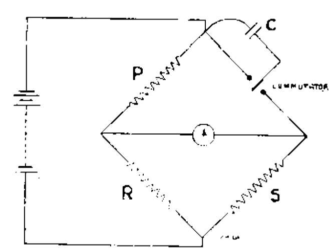


Fig. 78

$$C = \frac{2\pi R}{\omega PS}\left\{\frac{1 - \dfrac{R^2}{(R + P)\ (R + S + g)}}{1 + \dfrac{Rg}{P\,(R + S + g)}}\right\} \text{ where } \omega = 2\pi \times \text{frequency of commutator.} \qquad (33)$$

The bridge, though not strictly an alternating current one, does give values of capacity corresponding to a particular wave form at a particular frequency. The wave form is approximately square-topped, and therefore the results obtained are not so easily interpreted as the results which are obtained on a bridge in which the detector is selective.

[1] J. Clerk Maxwell, *Electricity and Magnetism*, 2nd Ed., 776-777.

SOME APPLICATIONS OF THE MOULLIN VOLTMETER

This low-reading patent voltmeter of sensibly infinite resistance (see pages 31 to 33) has a wide range of applications; a few typical examples at high frequencies are mentioned below.

(1) Use as a High Frequency Milliammeter.

By measuring the potential developed across a known inductance or capacity, the current can be calculated if the frequency is known, and under reasonably favourable conditions as to the value of the inductance and the frequency, either type of voltmeter can be used to measure currents some twenty times smaller than can be measured by any other type of portable instrument. The voltmeter can be used as an indicator of resonance in a circuit which is energised inductively from an ordinary buzzer-driven wavemeter. The uniformity of scale makes it a convenient instrument when plotting resonance curves or measuring resistances by substitution.

(2) Direct Measurement of Small Self and Mutual Inductances.

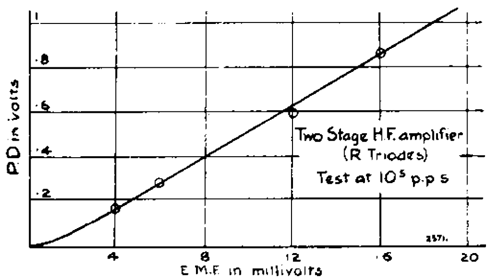


Fig. 79

Inductances of the order of a microhenry can be directly measured by either type of voltmeter by passing through them a high frequency current of about half an ampere in value. For example, the calculated value of the inductance of a coil consisting of 2 turns 6 cm. dia. of 32 S.W.G. wire, is $1{\cdot}86\,\mu H$; the value measured by the voltmeter and an ammeter was $1{\cdot}80\,\mu H$ at $1{\cdot}5 \times 10^5$ cycles. This method has been used to measure the value of small mutual inductances either by observing the E.M.F. set up in one coil by a known current in the other coil, or by measuring the self inductance of the two coils joined in series. A mutual inductance of $0{\cdot}8\,\mu H$ has been successfully measured in this way. The voltmeter is also useful for measuring the impedance drop across low frequency dynamometer ammeters, or current transformers.

(3) Measurement of the Amplification produced by Triode Amplifiers.

The voltmeter is useful in constructing high frequency amplifiers, for the amplification ratio can be directly measured. Type B is most suitable for use with resistance amplifiers, for its reading will not be affected by the large steady P.D. existing across the anode resistance. In Fig. 79 is reproduced a curve connecting input and output voltages for a two-stage high frequency amplifier; the valves used are " R " pattern, with about $60V$ on the anode. This application of the voltmeter has been fully dealt with by Moullin.[1]

(4) Measurement of Signal Strength.

By interposing a simple two-stage amplifier between the voltmeter and the aerial tuning coil, and without resorting to retro-action in the aerial, signal E.M.F.'s of about $300\,\mu V$ at $3{\cdot}10^5$ cycles have been accurately measured, and signal E.M.F.'s of less than $50\,\mu V$ have been detected.[2]

(5) Determination of the Power Factor of Condensers.

The power factor of a condenser can be determined by measuring, by a type B voltmeter, the P.D. across the diagonal of a balanced " condenser bridge," of which the condenser to be tested forms one arm.

Apparatus required:—A.C. source of any required frequency value ϵ volts (R.M.S.), equal low induction resistances R_1 and R_2 (page 10); variable air condenser, capacity C, having zero power factor; V is Moullin voltmeter type B. C_1 is the capacity of the condenser under test, its imperfection being represented by resistance r. The connections are made as in Fig. 80.

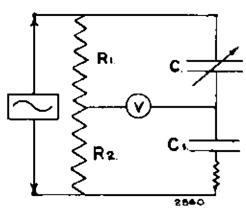


Fig. 80

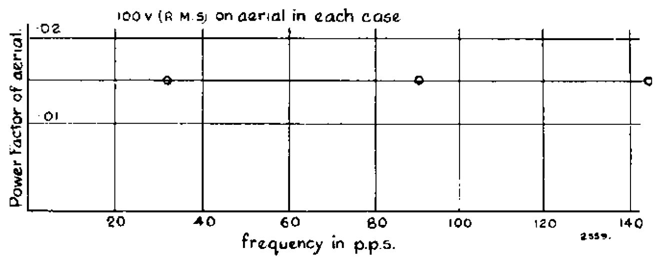


Fig. 81

If the condenser C_1 has a power factor, the P.D. across it will differ slightly in phase from the P.D. across R_2, and even though C is adjusted to be equal to C_1, a minimum rather than a zero reading will be obtained on V. This reading will be equal to the vector difference between the P.D. across C_1 and the P.D. across R_2. As long as the vector difference is small compared with ϵ, the ratio $\frac{2V}{\epsilon}$ will measure the angle by which the phase of the current through the condensers departs from the ideal " quad-phase " condition, or, in other words, the power factor of the condenser C_1. For a given value of V, the smallest angle which can be measured depends simply on the value of ϵ; $0{\cdot}5V$ is the smallest value that can be read with an accuracy of 5 per cent., so that the smallest measurable angle is about $\frac{1}{\epsilon}$ radians, or, if ϵ is $300V$, about 12 minutes of arc. The accuracy of the method has been tested by using an air condenser for C_1, and inserting a known resistance for r; under these conditions, $rwC/2$ should equal $\frac{2V}{\epsilon}$.

Example:— $C = C_1 = 5000$ micro-microfarads.

$r = 10000$ ohms.

Frequency $= 90$ cycles.

$$\therefore \frac{rwC}{2} = 0{\cdot}0141, \text{ where } w = 2\pi \times \text{frequency}.$$

The observed values of V and ϵ were $1{\cdot}5V$ and $212V$ respectively.

$$\therefore \frac{2V}{\epsilon} = 0{\cdot}0142.$$

This method has been used to measure the power factor of an aerial, and incidentally it forms a convenient way of measuring the capacity of an aerial. Fig. 81 shows the power factor of the aerial at the Cambridge University Engineering Laboratory at frequencies ranging from 30 cycles up to 150 cycles, the voltage on the aerial being $100V$ in each case.

[1] E. B. Moullin, Paper read before Inst. Elect. Engs., Dec., 1922.
[2] E. B. Moullin, *Journal Inst. Elect. Engs.*, 1922, lxi. 67.

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