CHAPTER XIII.—RADIO-FREQUENCY MEASUREMENTS

The wavemeter

1. A wavemeter is an instrument which is used to adjust a transmitter or receiver to a desired frequency, or alternatively to measure the frequency to which the transmitter or receiver is adjusted. The term wavemeter arose from the former practice (now confined to very short waves and to discussions of aerial design) of referring to the wavelength of an oscillation rather than its frequency. Wavemeters used in the service may be divided into two classes :—

- (i) Absorption wavemeters.
- (ii) Heterodyne wavemeters.

The absorption wavemeter

2. This instrument is chiefly used to measure the frequency of the oscillation generated by a transmitter, and by a process of repeated readjustment to ensure that the desired frequency is radiated. It consists fundamentally of two portions, first a closed oscillatory circuit, the natural frequency of which may be varied over a certain range by variation of the value of inductance or capacitance, or both. For all possible settings of the adjustable component or components, the frequency of the circuit is accurately determined and recorded, either directly upon a scale attached to the variable condenser or inductance, or upon a chart which shows the frequency corresponding to any setting of the instrument. The circuit is therefore said to be calibrated. If only a comparatively narrow frequency band is to be covered, the oscillatory circuit may consist of a fixed value inductance and a variable condenser, while if a wide band is to be covered the inductance also may be adjustable by means of tappings. It is of interest to note that the residual capacitance (i.e. that of the circuit when the condenser is set to its minimum value), is generally of the order of one-tenth the maximum value of the condenser, so that with any inductance whatever, the frequency range is about 1 to $\sqrt{10}$ or say 1 to 3. It is generally desirable, in calibration, to ignore the first and last ten degrees of the scale, so that the useful range of an ordinary variable condenser is only 160° instead of 180°, and the frequency range covered with a given inductance is generally only of the order of 1 to 2·75, e.g. 500 — 1,400 kc/s. In certain designs, a continuously variable inductance is used in conjunction with a bank of fixed-value condensers.

Resonance indicators

3. The second essential portion of an absorption wavemeter is some device which will indicate the presence of an oscillatory current in the circuit, and its relative magnitude ; this may be called the resonance indicator. By this means the wavemeter may be adjusted to resonance with an oscillating circuit. In use the wavemeter is held in proximity to the latter, and its oscillation constant (i.e. L C value) is varied until the oscillatory current in this circuit is a maximum, as shown by the resonance indicator. The frequency of the oscillation is then identical with that to which the wavemeter is adjusted. The required degree of coupling between the oscillating circuit and the wavemeter depends upon the magnitude of the oscillatory current, and upon the sensitivity of the indicating device. To all intents and purposes, then, the absorption wavemeter is merely an extremely portable receiver of low sensitivity. A large number of indicating devices have been used, but it is only necessary to describe a few typical ones, namely :—

- (i) Incandescent lamp.
- (ii) Hot-wire ammeter or thermo-ammeter.
- (iii) Neon tube.
- (iv) Valve rectifier and micro-ammeter.

The incandescent lamp

4. This indicator was used in the No. 3 wavemeter formerly employed in aircraft. The lamp is usually of the miniature metal-filament type, rated at about ·25 watts 2·5 volts, and its resistance is about 10 ohms when hot. It is connected either directly in series with the oscillatory

circuit, or in an untuned circuit which is inductively coupled to the latter; as in fig. 1a and 1b respectively. Obviously, in order to raise the filament to its maximum safe incandescence, an E.M.F. of rather more than 2·5 volts R.M.S. must be induced in the oscillatory circuit. In use, however, the wavemeter should be withdrawn until the filament is barely glowing, when a much sharper resonance indication is obtained than when the lamp burns at full brilliancy. As a matter of interest, it may be noted that the resistance of the lamp is lower at low temperature than at high, and consequently the damping of the oscillatory circuit less, whereas if a carbon filament lamp is used the opposite is the case, hence the preference for a metal-filament lamp.

Current meter

5. A hot-wire ammeter or thermo-ammeter may be used in place of the lamp, provided it is sufficiently sensitive to give an appreciable deflection with a current of about 100 milliamperes. Such an instrument offers no advantage over a metal-filament lamp, and as it is expensive and delicate, this resonance indicator has no present service application.

Neon tube

6. The neon tube is without doubt the most generally useful of all indicating devices. It consists of a glass bulb in which are enclosed a pair of electrodes. The tube may be designed to fit an ordinary miniature bayonet joint or Edison screw lamp holder. The bulb is first evacuated to a high degree and a small quantity of neon gas is then introduced. When the P.D. between the electrodes exceeds about 180 volts, the gas becomes ionized and therefore partially conductive; a small convection current then flows between the electrodes, and the gas becomes incandescent, emitting a characteristic reddish-orange glow. Once the ionization has been initiated it will persist even if the P.D. between the electrodes is reduced to about 140 volts. As the tube is a potential-operated device it must be connected between two points which have a high P.D., i.e. in parallel with the capacitance of the wavemeter circuit (fig. 1c) and not in series as were the devices previously mentioned. The E.M.F. induced in the wavemeter must be of the order of 1 volt R.M.S., and with a circuit of moderately high magnification, say about 140, the condenser peak voltage will be rather more than 180 volts which is sufficient to " strike " the lamp.

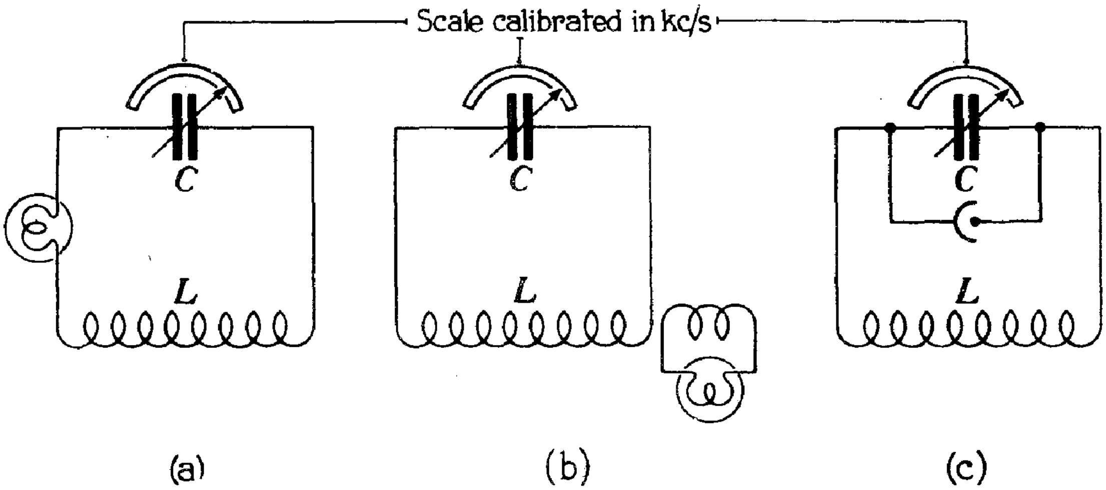


Fig. 1, Chap. XIII.—Connections of incandescent lamp and neon tube for resonance indication.

7. All the above devices possess the disadvantage that the presence of the indicating device increases the damping of the oscillatory circuit, and consequently the sharpness of resonance. The discrimination of the wavemeter, that is, the smallest difference of frequency which can be detected, depends upon the sharpness of resonance of the circuit as well as the characteristics of the indicating device. As regards the latter, the neon tube gives better discrimination than any form of apparatus depending upon the heating effect of the current.

Valve rectifier

8. (i) The form of rectifying detector most suitable for use as a resonance indicator is a triode valve used as a lower anode-bend detector. The circuit of a typical instrument is given in fig. 2, in which *L*, *C*, constitute the oscillatory circuit, T is a triode, the anode circuit of which contains a microammeter A reading up to about 250 or 500 microamperes, and a H.T. battery of from 10 to 60 volts. The grid is maintained at a suitable negative potential with respect to the filament, so that the normal anode current is extremely small, e.g. one microampere. When an oscillatory E.M.F. is induced in the coil *L*, and a corresponding P.D. between grid and filament of the valve, the resulting changes of anode current are unsymmetrical; a rectified current then flows in the anode circuit, its magnitude being indicated by the meter. As the maximum grid-filament P.D. will be developed when the input circuit is tuned to the frequency of the inducing source, resonance is indicated by maximum reading of the microammeter. This resonance indicator possesses an important advantage over those previously described in that it imposes no appreciable damping upon the input circuit, provided that the anode circuit is of negligible impedance compared to the anode A.C. resistance of the valve. A small effective capacitance will be added in parallel with the input circuit, and this will not be the same for valves of slightly different characteristics. It is a simple matter to allow for this by including a small "trimming" condenser C_0 (fig. 2) in parallel with C so that slight adjustments may be made to compensate for an exchange of valves without alteration to the calibration. Where such a condenser is fitted, it must never be interfered with except by the person authorized to restore the calibration after such an exchange has been made. It is usual to supply two or more valves with the wavemeter, each bearing a serial number showing with which particular instrument they are to be used. These valves are so chosen that either may be used without affecting the calibration, and it is only necessary to adjust the "trimmer" when the initial supply of valves is exhausted. If care is taken to switch the filament off as soon as the wavemeter is finished with, the valve should have a very long life. All valves should be treated with care, but those supplied with wavemeters should receive particular consideration.

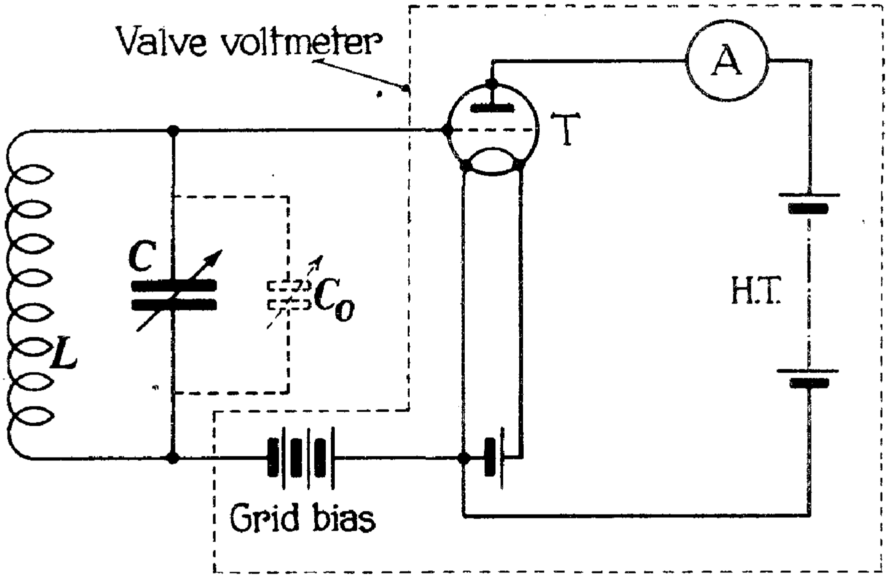


FIG. 2, CHAP. XIII.—Wavemeter with rectifier as resonance indicator.

(ii) This type of resonance indicator is much more sensitive than any of the other types, a grid-filament P.D. of about 2 volts being sufficient to give full scale deflection, i.e. with an input circuit magnification of 100, the induced E.M.F. need only be ·02 volt. In other words the sensitivity is about 100 times that of the neon tube while its discrimination is at least twice as good. When used for very high frequencies, a very open scale may be obtained by using a continuously variable inductance and a fixed condenser. A suitable type of inductance is that in which a radial arm is carried round each turn of the inductance in succession by a screw thread of coarse pitch (Chapter II).

Heterodyne wavemeter

9. The heterodyne wavemeter consists essentially of an oscillatory circuit which is maintained in oscillation by a thermionic valve, the triode being generally used. This wavemeter has a wide field of employment since it can be used to tune a receiver as well as a transmitter. When tuning a transmitter, the wavemeter is used as an autodyne receiver, and telephone receivers are introduced into the anode circuit of the valve, which acts as a detector in addition to maintaining the oscillation in its associated circuits. When used to adjust a receiver, the wavemeter acts as a transmitter of very low power, and having been adjusted to oscillate at the desired frequency, the receiver is easily adjusted to the latter. The circuit diagram of a typical heterodyne wavemeter is shown in fig. 3. Oscillations are maintained by the triode T_1 and the oscillatory circuit is of the Hartley type, consisting of any one of a series of plug-in coils, in order to cover a wide frequency range. The two inductances L_1, L_2 which constitute this plug-in unit, are wound side by side upon a suitable former, and the whole winding is tuned by the variable condenser C_1, while the condenser C_2, which is of the non-inductive type and of large capacitance compared to C_1, acts as a mains condenser. The grid is given a small initial positive bias by means of the potentiometer R_2, and a grid leak R_3 and grid condenser C_3 are fitted in order to give a negative grid bias in the oscillatory condition. This combination ensures that the inception of oscillations occurs on the comparatively steep portion of the valve characteristic. As the oscillation increases in amplitude, however, the grid becomes negatively biassed, and the grid-filament input conductance tends to assume a constant value. As stated in chapter IX this constancy is absolutely necessary if the frequency of the oscillation is to be unaffected by variation of L.T. and H.T. supply voltages.

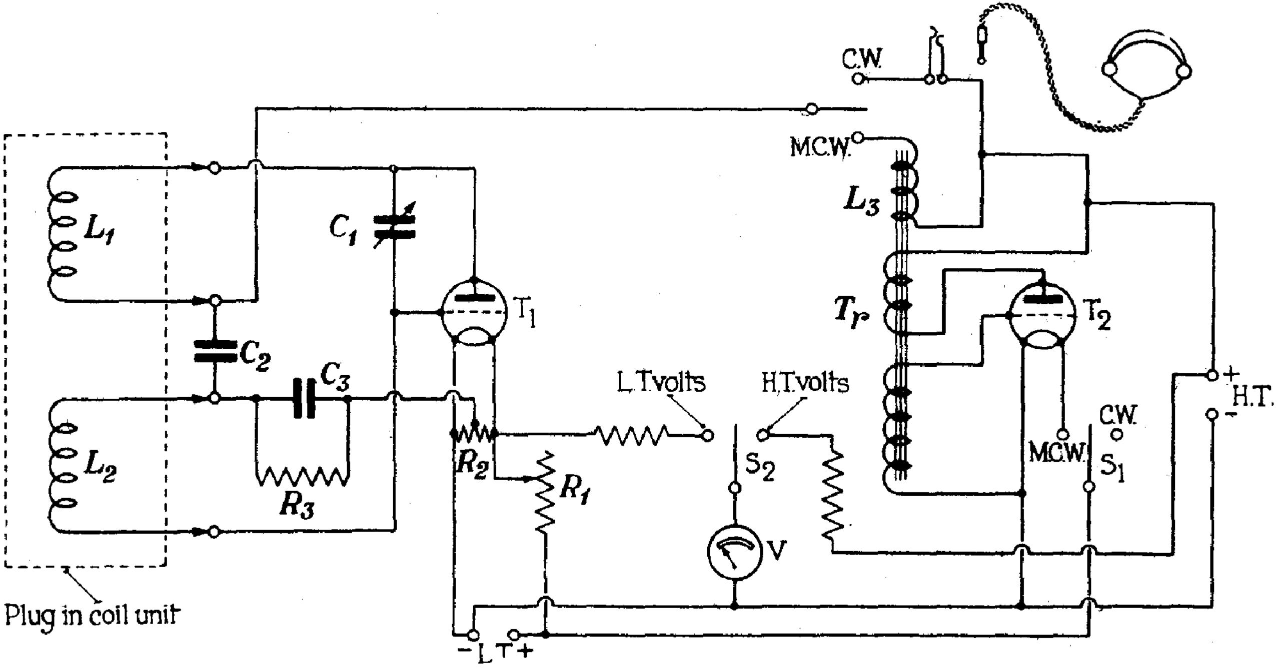


FIG. 3, CHAP. XIII.—Typical heterodyne wavemeter.

10. The variable condenser usually has a maximum capacitance of about ·0005 μF, and its scale is graduated in degrees, a slow motion drive and vernier scale being often provided in order that the setting may be determined to 0·1 degree. The calibration of this scale, for each

particular plug-in coil, is recorded on a chart, the method of checking the calibration being detailed later. It is essential that the operating conditions under which calibration is performed should be reproduced as accurately as possible when the wavemeter is in use, and this entails that the H.T. voltage shall not differ by more than about 5 per cent. and that the filament emission should be maintained to an even higher accuracy. For this reason it is usual to fit a voltmeter by which both the filament voltage and H.T. voltage may be checked. In the instrument shown in the diagram the filament voltage is adjusted to a definite value, say 5 volts, by the rheostat R_1, the voltmeter being connected in parallel with the filament, and the H.T. voltage is then checked while anode current is flowing by throwing over the switch S_2. Suitable series resistances are fitted so that the voltmeter is direct reading for either of the two voltages.

Use of heterodyne wavemeter

11. (i) In tuning a transmitter, if exceptional accuracy is not required, it is sufficient to operate the transmitter while listening in the telephone receivers of the wavemeter. The condenser of the latter is then adjusted to the dead space and the frequency read from the calibration. In this process it is usually essential to remove the wavemeter to a considerable distance from the transmitter, otherwise the latter will pull the wavemeter oscillation into resonance and no heterodyne note will be heard. The width of the dead space is proportional to the E.M.F. induced by the transmitter, and by sufficiently reducing the coupling between transmitter and wavemeter, may be limited to about 200 cycles per second on either side of the resonant frequency. With the loosest possible coupling, a measurement made by the ordinary or zero-beat-note method may therefore be in error by about 200 cycles per second, no matter what the absolute frequency may be. The percentage error however is larger on low than on high frequencies.

(ii) When tuning an oscillating receiver, the same procedure may be followed, but it is generally more convenient to set the wavemeter in oscillation at the desired frequency and to tune the receiver to the wavemeter emission, just as if the latter were due to a distant high-power transmitter instead of an immediately adjacent, low-power one. In order that receivers designed for modulated-wave reception may be tuned, it is desirable to arrange for the wavemeter to emit modulated waves. In the instrument illustrated this is achieved as follows. The valve T_2 is arranged as an audio-frequency oscillator, its filament being heated when the filament switch S_1 is set to " M.C.W." Instead of the telephone receivers, the coupling coil L_3, which is wound on the core of the audio frequency transmitter T_r, is now in series with the H.T. supply to the valve T_1. An audio-frequency oscillatory flux is set up in the core of the transformer, and the anode voltage of the oscillator valve T_1 varies about its mean value. The amplitude of the radio-frequency oscillation varies correspondingly, and the action is to all intents and purposes the same as in choke control modulation (Chapter XII). Alternatively, the modulator valve may be dispensed with and the grid condenser and leak given such values that the " squegger " type of oscillation is maintained by the oscillator valve. The disadvantages of this device are first, the difficulty of choosing values for C_3, R_3, which will maintain this form of oscillation over a wide frequency range, and second, the calibration will not maintain a high degree of constancy under these conditions.

Tuning by double beat method

12. Provided that the initial accuracy of the wavemeter is sufficient, the percentage accuracy on low frequencies can be improved by utilizing what is called the double beat method of tuning. This requires the use of an additional oscillator, which need not be calibrated. The principle of the method is as follows. Suppose a transmitter to emit a frequency f_T and the wavemeter to emit a frequency f_W, then owing to the rectifier action in the wavemeter a beat note of frequency $(f_T \sim f_W)$ is perceived. If the additional oscillator emits a frequency f_o and the transmitter is inoperative, the beat note in the wavemeter telephones will be $(f_W \sim f_o)$ cycles per second. When the emissions of both transmitter and oscillator are simultaneously received, both these beat notes will be heard, and in addition a third beat note which is caused by the heterodyne effect of the two difference frequencies.

13. (i) The procedure for adjusting the frequency of a transmitter to a predetermined figure by this method is as follows. Set up the wavemeter in accordance with its particular operating instructions, setting the frequency to the exact figure desired. A valve oscillator such as a syntonizer, or Receiver type R.64 with screening cover removed, is also adjusted for operation on the desired range. Listen in the telephones of this oscillator and adjust it to the dead space of the wavemeter emission. Press the key of the transmitter and adjust its frequency until a beat note is heard in the oscillator telephones, and bring this also into the dead space by adjustment of the transmitter. Do not vary the oscillator tuning during this operation. When this adjustment has been made, however, the second oscillator setting is varied slightly. As a rule, two distinct heterodyne beat notes will then be heard. By varying the transmitter frequency, these two notes are made to approach each other and a second beat will be established between them. This second beat becomes lower and lower in pitch and finally becomes zero, when the transmitter frequency is exactly that of the wavemeter. For example suppose the transmitter is to be tuned to 21,000 cycles per second. Then $f_W = 21{,}000$. Bring the oscillator frequency near to this, say $f_o = 22{,}000$, and adjust the transmitter as above to give a beat note with the oscillator, e.g. $f_T = 21{,}500$. We then have $f_W \sim f_o = 1{,}000$, $f_T \sim f_o = 500$. Now suppose f_T is shifted to 21,200 without changing f_W and f_o. Then $f_W \sim f_o = 1{,}000$, $f_T \sim f_o = 300$ and we get a second beat of 700. Shift f_T say to 21,100 ; $f_W \sim f_o = 1{,}000$, $f_T \sim f_o = 900$, and the second beat = 100. Shift f_T say to 21,020 ; $f_W \sim f_o = 1{,}000$, $f_T \sim f_o = 980$, the second beat = 20 and so on. Eventually we may adjust f_T to 21,001, $f_W \sim f_o = 1{,}000$, $f_T \sim f_o = 999$, and we get a second beat of one cycle per second. It is therefore possible after a little practice to adjust the transmitter almost exactly to the frequency of the wavemeter. There is a possibility that the second beat note may vanish owing to f_W and f_T being equally spaced above and below f_o, and to guard against this a check may be made by changing the frequency of the oscillator when the condition of zero double beat is obtained. If the transmitter and wavemeter are exactly in resonance, the single beat note will change but no double beat will re-appear.

(ii) To check the calibration of a wavemeter the double beat method may be used in combination with certain standard frequency transmissions, particulars of which are announced from time to time in Air Ministry Orders. The standard transmission takes the place of the wavemeter in the above explanation while the wavemeter is treated as the transmitter.

Tuning by harmonics

14. The range of a wavemeter may be extended to frequencies higher than those of its fundamental calibration by employing the harmonics of its oscillation. For this reason the circuit design is generally such that appreciable harmonics exist up to the 10th or even higher orders. Before attempting to use a wavemeter in this way for the first time, it is advisable to observe the relative intensity of the harmonics, e.g. by listening in the wavemeter telephones while rotating the tuning dial, in the neighbourhood of an oscillating receiver. As both oscillators produce harmonics, a large number of " chirps " are observed in this process, not only due to the fundamental of one oscillation and harmonics of the other but between say the second harmonic of one and the third, fourth, etc., of the other. A characteristic of these is the exceedingly minute portion of the scale in which the whole gamut of beat notes is perceived. The use of harmonics in tuning is best illustrated by a concrete instance. Suppose a transmitter to be in oscillation at a frequency which is known to be in the region of 18,000 kc/s, and the upper frequency limit of the wavemeter to be only 9,000 kc/s. Listening in the wavemeter telephones, note the successive readings at which " chirps " are heard. It is a good plan to sweep over the dial carefully and note approximately the location of each. Then repeat the process, approaching each point as slowly as possible, and taking full advantage of any slow-motion drive which may be fitted to the condenser, note the zero beat point of each harmonic as accurately as possible. Next tabulate the corresponding frequencies by reference to the calibration, as in the first two

columns of the table below. The successive frequencies at which the dead space of each " chirp " occurs should now be multiplied successively by a series of consecutive integers thus :—

(1) 6,100 (× 2 = 12,200)
(2) 5,632 (× 3 = 16,896)
(3) 5,230 (× 4 = 20,920)
(4) 4,574 (× 5 = 22,870)
(5) 3,661 (× 6 = 21,966)
(6) 3,052 (× 7 = 21,364)
(7) 2,614 (× 8 = 20,912)
(8) 2,288 (× 9 = 20,592)
(9) 2,034 (×10 = 20,340)
(10) 1,831 (×11 = 20,141)

The products shown in the right-hand column increase in value and then decline. This is an indication that beats caused by higher harmonics of the transmitter have been included in the series, frequencies (2) and (3) being suspect. The multiplication should be repeated, ignoring these.

(1) 6,100 (× 2 = 12,200)
(2) 4,574 (× 3 = 13,722)
(3) 3,661 (× 4 = 14,644)
(4) 3,052 (× 5 = 15,260),
etc.

This series is in an increasing progression throughout, showing that the wavemeter harmonics are of a higher order than those ascribed. If however the multiplication is repeated thus :—

(1) 6,100 (× 3 = 18,300)
(2) 4,574 (× 4 = 18,296)
(3) 3,661 (× 5 = 18,305)
(4) 3,052 (× 6 = 18,312)
(5) 2,614 (× 7 = 18,298)
(6) 2,288 (× 8 = 18,304)
(7) 2,034 (× 9 = 18,306)
(8) 1,831 (×10 = 18,310),

the consecutive products now closely approximate to 18,300. The mean of the eight results gives the transmitter frequency as 18,304 kc/s, the average error being about 5 kc/s. The " chirp " at 5,632 kc/s is easily seen to be caused by the beating of the 4th harmonic of the transmitter (73,220 kc/s) with the 13th harmonic of the wavemeter, while that at 5,230 kc/s is due to the second harmonic of the transmitter (36,610 kc/s) and the 7th of the wavemeter. If the transmitter is to be adjusted as accurately as possible to 18,000 kc/s, the wavemeter should now be set to exactly 6,000 kc/s, and the transmitter carefully readjusted to give a zero beat at this setting. It is advisable to have another check run of at least five harmonics, and take the mean frequency as that of the transmitter. From the foregoing it is seen that some little care must be exercised in interpreting the results obtained by harmonic tuning. In practice however, the " chirps " caused by transmitter harmonics are generally weaker than those caused by its fundamental and they are easily rejected after a little experience.

Combination of heterodyne and absorption meters

15. A well-designed wavemeter of the neon tube or valve rectifier type is capable of much higher accuracy than can be achieved in a portable heterodyne wavemeter. In cases where a wavemeter of the former type is supplied for the purpose of transmitter tuning, the receiver can

be tuned with the same degree of accuracy, provided that some form of heterodyne oscillator is available. The calibration of the latter is entirely ignored, and the procedure is as follows. Let us suppose it is desired to tune an oscillating receiver to a given frequency. First the transmitter is tuned to this frequency by means of the absorption wavemeter, using an artificial aerial where necessary. If the receiver is well screened, and fairly remote from the transmitter, it may be possible to tune the receiver directly to the transmitter, and nothing further is required. The transmitter and receiver, in situ, may however be interconnected in such a manner that the send-receive switch renders one or the other inoperative, and the heterodyne oscillator is then employed in the following manner. After tuning the transmitter to the desired frequency, the oscillator is syntonized with the transmitter by the dead space method, the telephone receivers being of course inserted in the heterodyne circuit. On switching over to "receive" the receiver may now be brought into resonance with the heterodyne oscillator in the usual manner, using the receiver telephones to obtain the dead space.

16. Where the receiver is of a non-oscillatory type, i.e. an R/T or I.C.W. receiver, either of the above methods may be used. If the receiver is to be tuned directly from the transmitter, the latter must be modulated by a source of sound of approximately constant amplitude, e.g. by fitting a small buzzer near the mouth-piece of the microphone, or even by holding a watch near it. If an additional heterodyne oscillator is employed, it must be tuned to the dead space as usual and subsequently, for the actual tuning of the receiver, must be caused to emit modulated waves.

17. An important application of the above expedient is to ensure that several aeroplanes which are to act in co-operation, are tuned to exactly the same frequency. This is achieved by tuning all transmitters with the same wavemeter, its frequency setting being rigidly clamped during transport from one aeroplane to another, and by tuning all the receivers to the emission of a single selected transmitter, generally that of the leader of the formation.

Double click method

18. An uncalibrated heterodyne oscillator may be brought into approximate resonance with an absorption wavemeter by what is called the double click method. The wavemeter is set to the desired frequency, and coupled to the oscillator. With the telephones in the latter circuit, if the heterodyne adjustment is varied, it will be found that a click is heard when resonance is nearly approached, and another click after passing the resonance point. These clicks are caused by sudden changes in anode current due to a fall in amplitude, or even, in the extreme case, to the cessation and re-establishment of oscillations. The reduction of amplitude is caused by the resistance load thrown into the oscillatory circuit of the oscillator by the presence of the absorbing circuit. When the coupling is very loose, this load is only small, the clicks are correspondingly faint and occur at closely adjacent points. With tighter coupling, so that the clicks are easily audible, they are separated by a greater distance on the scale. The resonant frequency is then taken as the mean of the two frequencies at which clicks occur.

Detection of clicks by current meter

19. (i) No great accuracy can be expected from the double click method under ordinary circumstances, first, owing to the difficulty of deciding the exact point at which each click occurs, and second, because to get clicks of good audibility, it is necessary to couple the two oscillatory circuits fairly closely. If it is possible to insert a sensitive moving coil instrument in either the anode or grid circuit of the heterodyne oscillator, the method becomes very sensitive and accurate. If a microammeter is available, it should be inserted in the grid circuit, as shown in fig. 4a, while if the only available instrument is a milliammeter, it should be inserted in series between the negative H.T. terminal of the oscillator and the negative terminal of the H.T. battery as in fig. 4b. The oscillator anode current should not exceed one-half of the maximum current for which the milliammeter is designed. The change of grid or anode current, at the point where the oscillation is wholly or partially suppressed, is shown by a violent flicker of the pointer. If the oscillator is fitted with a grid condenser and leak, the cessation of oscillations will be denoted

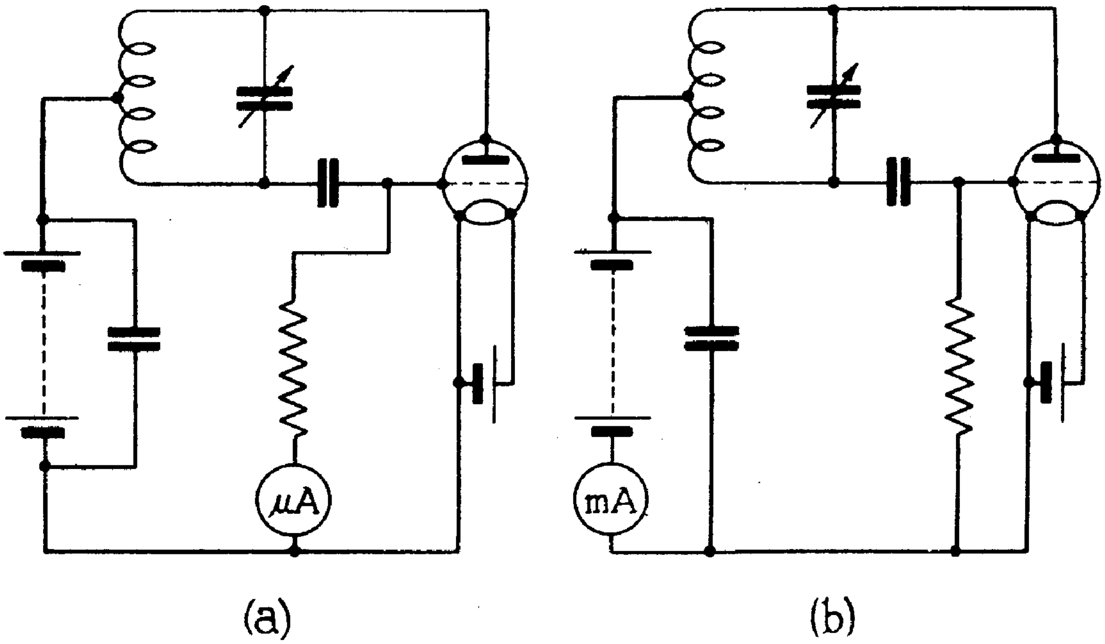


FIG. 4, CHAP. XIII.—Heterodyne oscillators with current meters as resonance indicators.

by a rise of anode current, and by a fall of anode current in the case of an oscillator without these components. Grid current usually falls on the cessation of oscillations in both types of oscillator.

(ii) The above information must not be regarded as an authority to interfere with the permanent wiring of a service wavemeter. It is intended to suggest a method of calibrating a heterodyne oscillator made up for the purpose of extempore measurements, such as are described in paragraphs 27 *et seq.*

The valve voltmeter

20. The resonance indicator described in paragraph 8, and enclosed in dotted line in fig. 2, is often referred to as a valve voltmeter, although strictly this term should only be applied if the microammeter scale is actually calibrated in volts. No calibrated valve voltmeter is at present standardized for service use, but where a suitable microammeter is available such an instrument is easily made up and calibrated. The voltmeter may then be used for the measurement of small radio-frequency or audio-frequency P.D's from 0·1 up to about 20 volts. Previous to the introduction of the valve voltmeter the measurement of such voltages was only possible in a well-equipped laboratory. The voltmeter can be so designed as to throw only a negligible load upon the circuit under investigation, and its indications are practically independent of frequency. It may therefore be calibrated at commercial frequency, using a potentiometer fed from the A.C. supply mains. Many different forms of instrument have been evolved for laboratory use, but only two will be dealt with here.

The anode-bend voltmeter

21. This is identical in principle with the resonance indicator previously described. The H.T. and grid bias voltages must be carefully chosen with respect to the valve and the particular anode current meter it is proposed to use. With most types of battery triode this form of voltmeter has a range of about 0 to 2 volts, and the grid bias should be about — 3 volts, in order to avoid grid current, which if allowed to flow will cause the meter to load the input circuit. The filament circuit should contain a rheostat with an off position, and care should be taken that the filament is never switched on unless there is a completely conductive path between grid

and filament, in order that the correct bias is always applied to the grid. The H.T. voltage should be so chosen that a just perceptible anode current flows when the grid and filament are directly connected, and only about one quarter of the filament rheostat is in circuit. This deflection of the microammeter will then be the zero of the voltage calibration, the scale zero being disregarded. The meter may be calibrated by means of a potentiometer consisting of a length of 22 s.w.g. eureka wire, rather more than 36 inches being required. This is connected to an A.C. source, in series with a suitable adjustable resistance and a hot-wire ammeter, the resistance being so chosen that the current can be varied between say 0·5 ampere and 2·0 amperes. The potentiometer wire may be stretched on a bench or table, and by means of a Wheatstone bridge or bridge-megger, two points on the wire are located between which the resistance is exactly one ohm. Terminals are fitted at these points and the intervening wire divided into ten equal parts. The input terminals of the voltmeter are connected to the potentiometer via one of the terminals and a sharp edged pricker. It is obvious that with a current of one ampere in the wire, the P.D. between the terminals is one volt, and any desired fraction of this can be tapped off. The corresponding deflection of the microammeter is then noted, successive readings being plotted on a calibration curve. The scale may be extended from one to two volts by increasing the current in the potentiometer wire to two amperes. The method of calibration is shown diagrammatically in fig. 5.

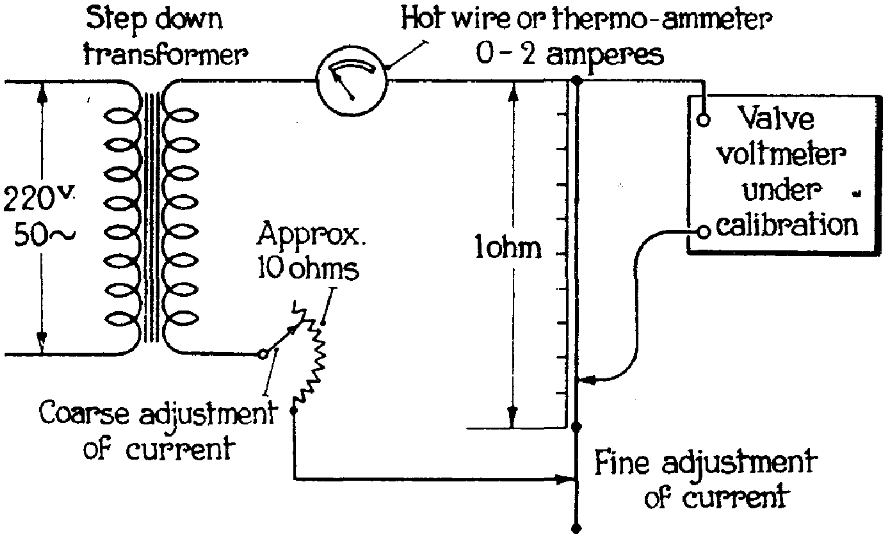


FIG. 5, CHAP. XIII.—Calibration of valve voltmeter.

22. When calibrated, it will be found that the scale is not uniformly divided, owing to the fact that the $I_a - V_g$ characteristic of the valve is curved. The linearity of the scale can be improved by the insertion of a non-inductive resistance of 30,000 to 60,000 ohms in the anode circuit. It is then necessary to connect a by-pass condenser of not less than ·1 μF between anode and filament. It should have mica dielectric and be non-inductive. The whole instrument may be assembled on a board or in a box. Once the meter has been calibrated, the calibration may be relied upon to within about 5 per cent., provided that the operating voltages—filament, grid bias, and H.T.—are the same as when calibrating.

Peak voltmeter

23. If it is required to measure radio-frequency or audio-frequency voltages between say 5 and 50 volts, without attempting a very high degree of accuracy, the arrangement shown in fig. 6 may be adopted. The valve D is a diode, or triode with grid and anode in direct connection, and C is a condenser of high insulation resistance ; for radio-frequency work its capacitance may be about ·0005 μF, and is not critical. Ignoring the presence of the resistance R and the

microammeter, it is seen that if an alternating voltage is applied to the input terminals, the condenser will charge until the P.D. between its plates is equal to the peak voltage at the terminals. With the resistance and microammeter connected as shown, this charge will leak away, and the average condenser P.D. is obtained from the product of the resistance R and the leakage current indicated by the microammeter. Provided the resistance is sufficiently large, the average condenser P.D. will only be a fraction of a volt below the terminal voltage. The instrument requires no calibration, but the value of the resistance should be so chosen that the voltage may be read directly from the microammeter scale by using a convenient conversion factor. For example, if $R = 10^5$ ohms and the microammeter reads $0 - 200$ microamperes, the average condenser P.D. is obtained by dividing the scale reading by 10, and the voltmeter has a range of 0 to 20 volts.

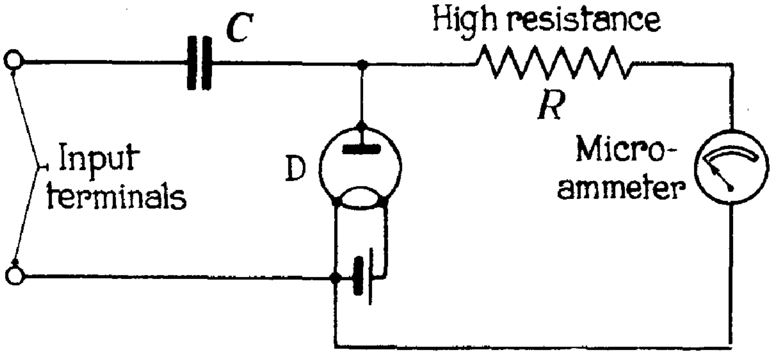


FIG. 6, CHAP. XIII.—Peak (diode) valve voltmeter.

24. Although no great accuracy can be expected of the instrument when used in the above manner, it may be calibrated by the method described in paragraph 21. This calibration will of course give R.M.S. and not peak values. Owing to the incorporation of the reservoir condenser C, the calibration is not independent of frequency. It may be taken that if the supply voltage is E, and the condenser voltage V,

$$V = \frac{\omega CR}{\sqrt{1 + \omega^2 C^2 R^2}}\, E.$$

Thus if $C = \cdot 001\ \mu F$, $R = 10^5$ ohms, and the meter is used to measure the voltage E of the 50-cycle mains, it will read

$$V = \frac{2\pi \times 50 \times \cdot 001 \times 10^{-6} \times 10^5}{\sqrt{1 + (2\pi \times 50 \times \cdot 001 \times 10^{-6} \times 10^5)^2}}\, E$$
$$\doteqdot \cdot 03\, E,$$

i.e. only one-thirtieth of the true voltage !

On the other hand, if a capacitance of $\cdot 2\ \mu F$ is used

$$V = \frac{2\pi \times 50 \times \cdot 2 \times 10^{-6} \times 10^5}{\sqrt{1 + (2\pi \times 50 \times \cdot 2 \times 10^{-6} \times 10^5)^2}}\, E$$
$$= \cdot 98\, E$$

i.e. an error of only 2 per cent.

25. If such a condenser were fitted permanently in circuit however, its comparatively large bulk would cause it to have appreciable capacitance to earth, and at high frequencies would constitute a path of low reactance in parallel with the grid and filament of the valve. This might introduce a serious error. The difficulty may be overcome by fitting a large condenser for

calibration at the supply frequency and substituting a small one for radio-frequency measurements. If the quantity ωCR remains the same the calibration will hold. For instance if $f = 50$, $C = \cdot 2\ \mu F$, $R \doteq 10^5$, $\omega C = 2\pi \times 10^{-5}$, $\omega CR = 2\pi$. At 10^5 cycles per second, the capacitance giving an equal admittance is

$$\begin{aligned} C_1 &= \frac{2\pi}{10^5 \omega} \\ &= \frac{2\pi}{10^5 \times 2\pi \times 10^5} \text{ farad} \\ &= \cdot 0001\ \mu F. \end{aligned}$$

The chief disadvantage of this form of voltmeter is its low input impedance, which is rarely greater than $\frac{R}{3}$ and may be lower still. For this reason it is preferable to use a reservoir condenser of small capacitance, but the resistance R must then be correspondingly large in order to keep ωCR as large as possible.

26. An interesting application of the principle of the peak voltmeter is to measure the most positive potential reached by the grid of a radio-frequency power amplifier. In fig. 7 the amplifier valve is denoted by T and it derives its excitation (of peak value $\mathcal{V}_g$) by means of an inductive coupling to the previous stage. The operating grid bias is supplied by means of a battery. The peak voltmeter consists of a diode D with its filament heating battery, a battery E, potentiometer P, moving-coil voltmeter and low-reading milliammeter. When the excitation reaches its positive peak, the grid of the triode is at a potential $E_g = \mathcal{V}_g - E_b$ volts above that of the filament (*see* Chapter XI). As the diode will pass current only if its anode is positive with respect to the filament, no current will flow through the milliammeter if the voltage V is greater than E_g. To measure the latter voltage therefore, the voltage V is reduced by means of the potentiometer until a very small current is detected, and the voltage is then again increased until the deflection of the milliammeter is reduced to zero. At this point, $V = E_g$. When used in conjunction with a potentiometer and battery in this manner, the diode is said to function as a " slide-back " voltmeter.

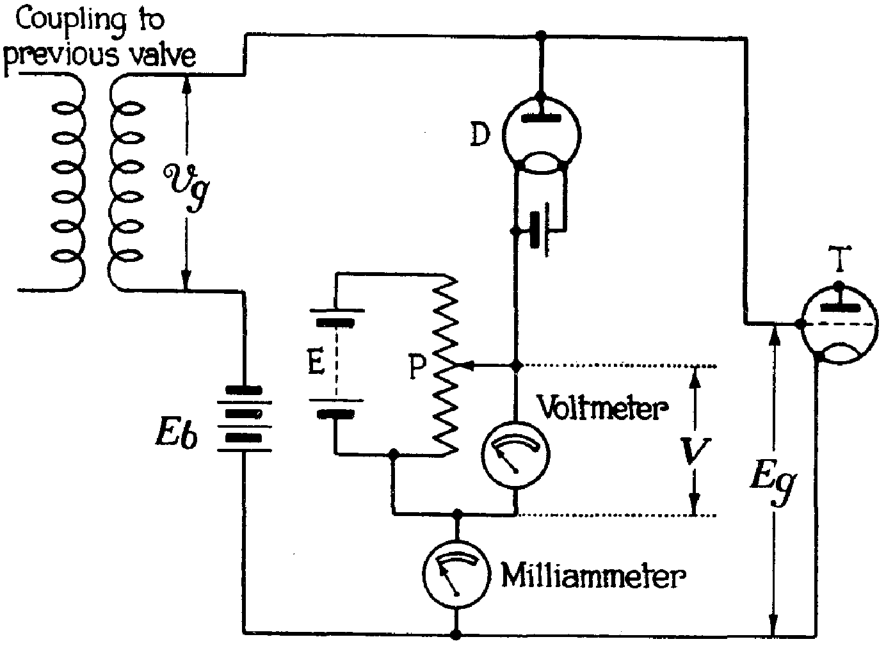


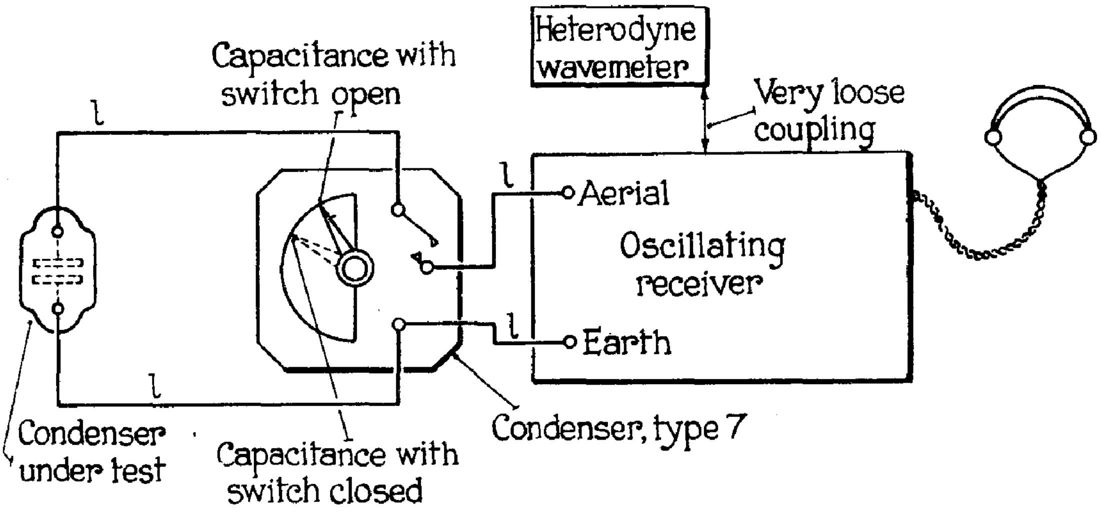
FIG. 7, CHAP. XIII.—Measurement of peak grid voltage of amplifier valve.

Measurements of inductance, capacitance and resistance

27. Occasions may arise, although rarely, when it becomes necessary to make measurements of these quantities ; great accuracy is seldom necessary and it is not possible with the apparatus generally available. It is possible however to achieve a good deal with the aid of (i) a reliable heterodyne wavemeter. (ii) a good air-dielectric variable condenser with semi-circular moving vanes, e.g. the service type 7 condenser, and (iii) a valve voltmeter of the anode-bend type. The type 7 condenser is sometimes calibrated both in scale degrees, 0° to 180°, and in "jars." The latter is a unit of capacitance equal to $\frac{1}{900}$ of a micro-farad, and is no longer used in the Royal Air Force. The latter calibration is generally sufficiently accurate for any measurement which is required in the field. If the scale is marked only in degrees, it may be assumed that the minimum capacitance (scale reading zero) is $\cdot 00005\ \mu F$, the maximum (scale reading 180°), $\cdot 00095\ \mu\text{F}$, and that the capacitance varies uniformly between these limits.

Measurement of capacitance

28. To measure the capacitance of a small (fixed value) condenser, connect the terminals of the type 7 condenser as in fig. 8 to the aerial and earth terminals of a self-oscillatory receiver such as the type R.64, in place of the normal aerial and earth, and set up a heterodyne wavemeter or syntonizer to operate in the desired frequency range. The type 7 condenser should be adjusted to a capacitance rather larger than the estimated capacitance of the condenser under test, and the receiver set in self-oscillation. The wavemeter is then adjusted to the frequency of the receiver by tuning it to the dead space, using the wavemeter telephones for this purpose. The fixed condenser is then connected in parallel with the type 7 condenser, and the capacitance of the latter reduced until the receiver and wavemeter are again in resonance. The capacitance of the fixed condenser is equal to the change in capacitance of the type 7 condenser. In all measurements of this nature, it is essential to reduce the dead space to the lowest possible range by using a very loose coupling between the wavemeter and the tuned circuit which is under test. This test is of particular value in the case of an internal disconnection in a small fixed condenser, which is otherwise difficult to diagnose. An intermittent connection is also sometimes revealed by sudden variation in the beat note, and the presence of abnormal losses such as are caused by a high resistance connection to one or more electrodes may cause the receiver to stop



NOTE: All connecting leads l to be as short as possible

FIG. 8, CHAP. XIII.—Measurement of capacitance of low value.

oscillating when the condenser is connected in circuit. If an appreciable increase of reaction is necessary to maintain oscillation the electrical efficiency of the condenser should be regarded with suspicion.

Self-capacitance and inductance of a tuning coil or R.F. choke

29. To measure these, the coil is connected in parallel with the calibrated condenser to form a closed oscillatory circuit, and a valve voltmeter, which need not be calibrated in volts, is connected to the condenser terminals. A radio-frequency E.M.F. is induced in the circuit by loosely coupling to a heterodyne wavemeter, the arrangement being shown in fig. 9. It may be necessary to place the wavemeter several feet away from the oscillatory circuit, but in any case the coupling should be only just sufficient to give an appreciable scale reading in the voltmeter when the two circuits are in resonance. The standard condenser is set to say 170° and the wavemeter frequency is adjusted to resonance with the oscillatory circuit as shown by the voltmeter. The capacitance of the condenser and the wavemeter frequency are noted; the condenser is then re-set to say 160°, the wavemeter frequency adjusted to resonance, and again noted. The process is repeated for various values of capacitance and a table compiled as under :—

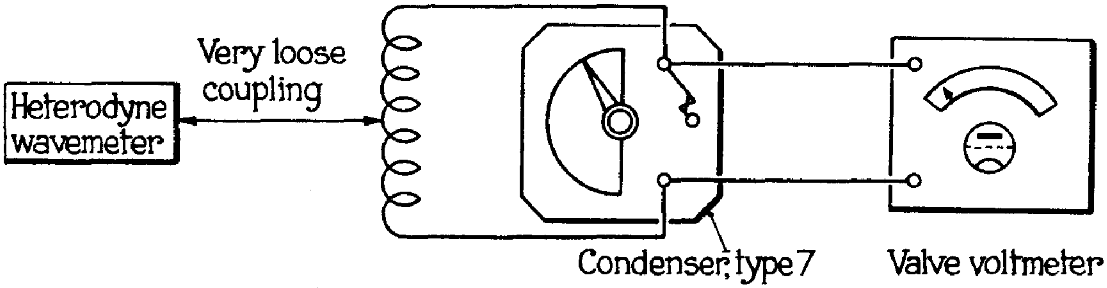


FIG. 9, CHAP. XIII.—Measurement of inductance and self-capacitance of coil.

f (Mc/s).	$\frac{1}{f}$	$\frac{1}{f^2}$	Added capacitance C ($\mu\mu F$).
·5	2	4	940
·52	1·92	3·7	850
·55	1·83	3·3	740
·57	1·75	3·06	700
·60	1·66	2·75	590
·69	1·45	2·1	430
·8	1·25	1·56	300
·9	·81	1·235	190
1·0	1·0	1·0	130

30. The corresponding values of added capacitance C and $\frac{1}{f^2}$ are plotted as shown in fig. 10. The points will be found to lie very nearly on a straight line, and the straight line lying most evenly between the points should be drawn. On extending this, it will be found not to pass through the origin; the intersection of this line with the $\frac{1}{f^2}$ axis gives the value of $\frac{1}{f^2}$ with no added capacitance, and from this the natural frequency of the coil alone is easily found. If the line is extended still further it cuts the capacitance axis on the negative side of the origin. This gives the value of capacitance which would exactly annul the self-capacitance of the coil, and

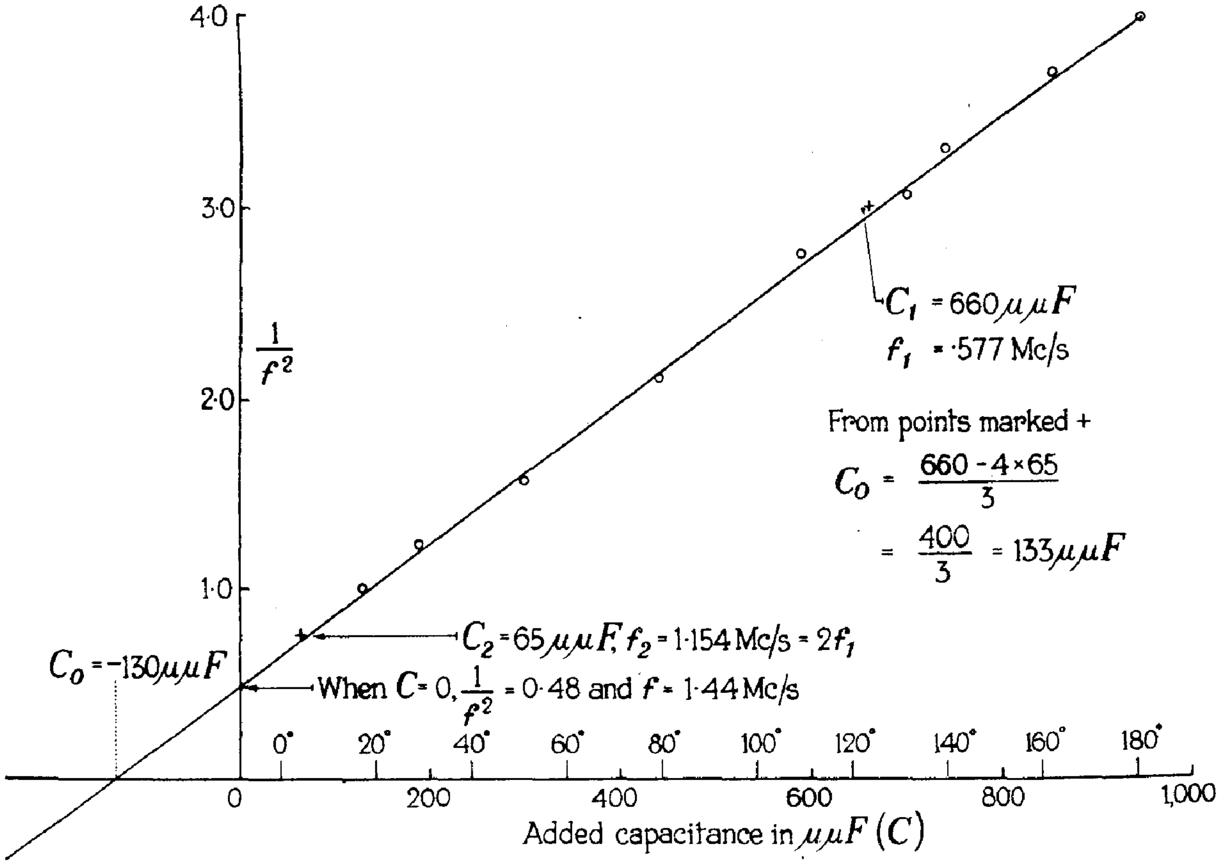


FIG. 10, CHAP. XIII.—Graphical derivation of L_o and C_o

the self-capacitance C_o is obviously equal in magnitude to this. In the diagram, the value of $\frac{1}{f^2}$, with no added capacitance, is ·48, and the self-capacitance 130 $\mu\mu F$. The inductance L_o is calculated from these values, using the relation $f = \frac{10^6}{2\pi\sqrt{LC}}$ where L is in microhenries and C in microfarads. Let f_o denote the natural frequency of the coil, then

$$f_o\ (\text{Mc/s}) = \frac{1}{2\pi\sqrt{L_oC_o}}$$

$$f_o^2 = \frac{1}{2^2\ \pi^2\ L_o\ C_o}$$

$$L_o\ C_o = \frac{1}{2^2\ \pi^2} \times \frac{1}{f_o^2}$$

$$= \frac{1}{39{\cdot}48} \times {\cdot}48$$

$$L_o = \frac{{\cdot}48}{39{\cdot}48} \times \frac{10^6}{130}\ (\mu H)$$

$$= 93{\cdot}5\ \mu H.$$

31. The disadvantage of this method is that the wavemeter has to be adjusted to resonance with the tuned circuit after each readjustment of added capacitance. The frequency must then be obtained from the calibration and its reciprocal is to be squared. Thus the arithmetical accuracy of the graph is generally poor. If the wavemeter has a pronounced second harmonic this disadvantage can be overcome as follows. First, add a fairly large capacitance C_1 to the tuned circuit, e.g. 670 $\mu\mu F$, and find its resonant frequency; call this f_1. Then, without disturbing the wavemeter setting, reduce the added capacitance while watching the valve voltmeter closely for a response to the second harmonic of the wavemeter frequency. If such a deflection is obtained, with a capacitance C_2, the circuit is tuned to a frequency $f_2 = 2f_1$. Since the inductance L_o is constant, it follows that

$$L_o (C_1 + C_o) = 4 L_o (C_2 + C_o)$$

$$\frac{C_1 + C_o}{4} = C_2 + C_o$$

$$\frac{C_1}{4} - C_2 = C_o - \frac{1}{4} C_o$$

$$C_1 - 4C_2 = 3C_o$$

$$C_o = \frac{C_1 - 4C_2}{3}$$

An example of this method is given in fig. 10. Here $C_2 = 65$ $\mu\mu F$, and the self-capacitance is found to be 133 $\mu\mu F$. This value of C_o, inserted in the formula $f_1 = \dfrac{1}{2\pi\sqrt{L_o (C_1 + C_o)}}$ will give the value of the inductance.

32. It may here be mentioned that in the absence of facilities for measurement, the following empirical rule may be used for single-layer solenoids, viz., the self-capacitance of a coil, in micro-microfarads, is equal to ·64 of the radius of the coil in centimetres. The natural frequency of the coil may be found by placing it in proximity to the heterodyne wavemeter, and listening in the telephones of the latter. As the wavemeter frequency is varied, a characteristic click should be heard when the natural frequency of the coil is passed through. On closer observation, it will be found that there are really two clicks, quite close together. They are caused by the reduction of amplitude of the wavemeter oscillation when the coil is in resonance, owing to the heavy damping then imposed upon the oscillator. The coil is in effect acting as an absorption wavemeter at this particular frequency. If the wavemeter is fitted with a sensitive meter in grid or anode circuit, resonance is indicated by a sudden flicker of its pointer (cf. paragraph 19).

Magnification of a closed oscillatory circuit

33. The magnification of a closed oscillatory circuit is easily determined by loosely coupling it to the heterodyne wavemeter. A calibrated valve voltmeter of the anode-bend type is connected across the condenser terminals of the oscillatory circuit, and the coupling adjusted so that the P.D. across the condenser is of some integral value near the upper limit of the voltmeter scale, e.g. 2 volts, when the wavemeter is exactly in resonance with the oscillatory circuit. Without altering the coupling, the wavemeter is then detuned until the condenser P.D. is reduced to ·707 of its maximum value, in this case, 1·414 volts. Let this be a frequency f_1 lower than the resonant frequency f_r. Sweep back through the resonant frequency, checking the peak value of voltage, and then detune to a frequency f_2, higher than f_r, at which the condenser P.D. is again ·707 of the maximum. The magnification χ is then given approximately by the formula

$$\chi = \frac{\omega L}{R} = \frac{f_r}{f_2 - f_1}.$$

Resistance of tuning coil or R.F. choke

34. If the coil is of such a shape that its inductance can be readily calculated, or can be found by the method previously explained, the resistance may be calculated from the magnification. If however it is required to measure the resistance independently, this can be performed as follows. It is first necessary to make up a set of sub-standard resistances, which must be of resistance wire of fine gauge, e.g. not less than 40 s.w.g. The resistance should be wound on a thin sheet of mica; a mica "card" about 2 in. by 4 in. may be used as a former, narrow slots about ½ in. deep being cut in each edge. The wire is then wound in these slots until the desired resistance is obtained. This winding will have very low inductance owing to the closeness of the wires forming each complete "turn" of wire. Copper wires not thicker than 30 s.w.g. may be used to connect the resistance in circuit, and a suitable holder is shown in fig. 11 together with a typical "card." The holder consists of a strip of bakelite slotted longitudinally to hold the card vertically, and the smallest obtainable terminals are used at each end to form binding posts for the interchange of resistances. The D.C. resistance of each should be measured by bridge-megger and it must be assumed that the R.F. resistance is the same as the D.C. resistance. This is the reason for stipulating that the finest available wire should be used. Eureka wire of 47 s.w.g. has a resistance of about 6 ohms per inch, while 40 s.w.g. has a resistance of about one ohm per inch. Where possible, of course, the resistance should consist only of a short straight wire. The approximate length for any given resistance may be found from Table I, Appendix A.

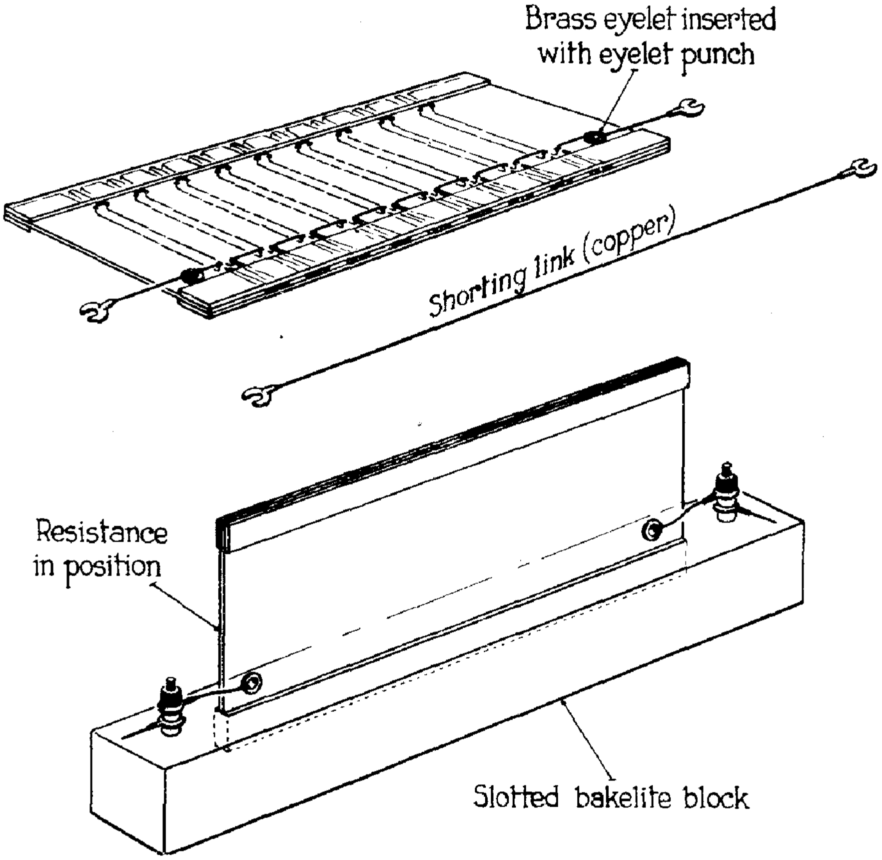


FIG. 11, CHAP. XIII.—Construction and mounting of sub-standard resistance.

The resistance-variation method

35. The resistance-variation method of measurement is illustrated in fig. 12. The coil of which the resistance is to be measured, a condenser of high electrical efficiency (i.e. negligible

resistance), and the resistance holder described above are connected to form a closed oscillatory circuit. A calibrated valve voltmeter of the anode-bend type is connected across the condenser terminals, and a heterodyne wavemeter loosely coupled to the coil. The circuit is tuned to resonance with the wavemeter, the coupling being adjusted so that the voltmeter reading is near the maximum of its scale. During this operation the resistance holder is occupied by a short piece of copper wire, the resistance of which may be regarded as negligible. If E is the voltage induced in the circuit by the wavemeter, $\frac{\omega_r}{2\pi}$ the resonant frequency of the circuit, C the capacitance of the condenser, V_1 the voltage across the latter, and R_1 the resistance of the circuit

$$V_1 = \frac{1}{\omega_r C} \times \frac{E}{R_1}.$$

A known resistance R_2 is now connected to the resistance holder in place of the short copper link, and the circuit retuned to obtain maximum deflection in the voltmeter. It is important

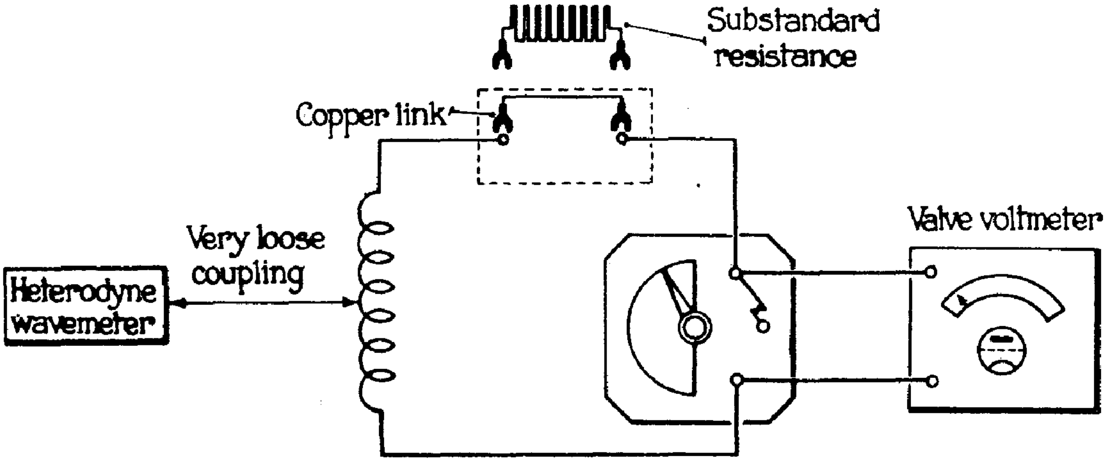


FIG. 12, CHAP. XIII.—Resistance-variation method of measuring R.F. resistance.

that the wavemeter, and the coupling between that instrument and the closed circuit, should not be disturbed in any way. On retuning, let the voltmeter reading be V_2. Then

$$V_2 = \frac{1}{\omega_r C} \times \frac{E}{R_1 + R_2},$$

assuming that the introduction of the resistance has not changed the value of tuning capacitance.

From the above expressions, if $\frac{E}{\omega_r C}$ is denoted by K,

$$V_1 = \frac{K}{R_1}$$

$$V_2 = \frac{K}{R_1 + R_2}$$

$$V_1 - V_2 = K\left(\frac{1}{R_1} - \frac{1}{R_1 + R_2}\right)$$

$$= K\left(\frac{R_2}{R_1\,(R_1 + R_2)}\right).$$

But
$$\frac{K}{R_1 + R_2} = V_2$$
$$\therefore V_1 - V_2 = V_2 \frac{R_2}{R_1}$$
$$R_1 = \frac{V_2}{V_1 - V_2} R_2.$$

It is advisable to check all measurements by adding at least two different known resistances.

36. The values of R_1 so obtained may differ from each other and the most convenient method of finding the probable value of R_1 is to plot $\frac{1}{V_2}$ against added resistance ; this procedure is analogous to that used in finding the self-capacitance of an inductive coil (paragraph 29). Suppose we obtain a set of readings as under :—

Added resistance (ohms)	V_2	$\frac{1}{V_2}$
0	2	·5
1	1·67	·6
2	1·43	·7
5	1·0	1·0
10	·67	1·5

On plotting $\frac{1}{V_2}$ against the added resistance, the points will be found to lie near a straight line, which should be drawn. On producing it to meet the " resistance " axis on the negative side of the origin, the intercept gives the value of negative resistance which will exactly annul the positive resistance of the coil, thus giving the value of the latter. In the above example, $R_1 = 5$ ohms.

37. The results obtained in this way may be very considerably in error owing to the effect of the self-capacitance of the coil. This error can be reduced by using a tuning capacitance very much larger than the self-capacitance. A correction may also be applied from the following considerations. If m is the ratio of the frequency f_r, at which the measurement is made, to the natural frequency f_0 of the coil alone, i.e. if $m = \frac{f_r}{f_0}$, it can be shown that the measured value R_1 is related to the true resistance R by the equation
$$R_1 = \frac{R}{(1 - m^2)^2}.$$

Taking as an example the coil referred to in paragraph 29, the natural frequency of which was found to be 1·44 Mc/s, suppose the resistance is measured with 590 $\mu\mu F$ in parallel, so that $f_r = \cdot 6$ Mc/s.

$$m = \frac{f_r}{f_0} = \frac{\cdot 6}{1 \cdot 44} = \cdot 416$$
$$m^2 = \cdot 173$$
$$(1 - m^2)^2 = \cdot 685$$
$$R_1 = \frac{R}{\cdot 685}$$
$$= 1 \cdot 43\ R.$$

If f_0 is known, as in the present example, the measured resistance may be corrected by using the above formulae. It it however preferable to make the measurement at a much lower frequency, e.g. $f_r = \cdot 25$ Mc/s. Then

$$m = \frac{f_r}{f_0} = \frac{\cdot 25}{1\cdot 44} = \cdot 1735$$

$$m^2 = \cdot 03$$

$$(1 - m^2)^2 = \cdot 94$$

$$R_1 = \frac{R}{\cdot 94}$$

$$= 1\cdot 065\ R.$$

The error is now only 6·5 per cent. If it is desired to keep the error due to self-capacitance alone to within 5 per cent., we must make $f_r \overset{=}{>} \cdot 158\ f_0$. Then

$$m \overset{=}{>} \frac{1}{6\cdot 32}$$

$$m^2 \overset{=}{>} \frac{1}{40} = \cdot 025 \text{ (approx.)}$$

$$(1 - m^2)^2 \overset{=}{>} (\cdot 975)^2 = \cdot 955$$

$$R_1 \overset{=}{>} \frac{R}{\cdot 955}$$

$$R_1 \overset{=}{<} 1\cdot 05\ R.$$

The total error will be greater than this and may be of the order of 10 per cent.

38. A new difficulty now rises in that the measured resistance is that at the frequency f_r, which in the above case is 288 kc/s, whereas a coil of 92·5 μH is most likely to be used in a band in the region of 1 Mc/s. The trouble is prominent in this particular case because the self-capacitance is comparatively large. If it were only one-tenth of the given value, or 13 $\mu\mu F$, the natural frequency would be about 4·55 Mc/s and a measurement at ·72 Mc/s, would require a correction for self-capacitance of about 5 per cent.

The reactance-variation method

39. This method obviates the necessity for a set of known resistances, but requires a calibrated variable condenser. The frequency at which the measurements are made must be known to a high degree of accuracy. The coil to be measured is connected as in the previous case (fig. 12) except that the resistance holder is omitted, and the wavemeter is again loosely coupled to the oscillatory circuit. The procedure in making a measurement is as follows. Set the wavemeter to a convenient frequency, $\frac{\omega}{2\pi}$, and tune the oscillatory circuit to exact resonance. Note the capacitance C_r and condenser P.D., V_r, at this point. Now detune the circuit slightly, noting the new capacitance C_1 and condenser P.D., V_1. Let the impedance of the de-tuned

circuit be $Z = \sqrt{R^2 + X^2}$. If E is the E.M.F. induced in the circuit by the wavemeter, and this is constant during the whole operation, we have

$$V_r = \frac{E}{\omega C_r R}$$

$$V_1 = \frac{E}{\omega C_1 Z}$$

$$\frac{V_r}{V_1} = \frac{C_1 Z}{C_r R}$$

$$= \frac{C_1}{C_r}\sqrt{1 + \frac{X^2}{R^2}}$$

$$\left(\frac{C_r\,V_r}{C_1\,V_1}\right)^2 = 1 + \frac{X^2}{R^2}$$

$$\frac{X^2}{R^2} = \left(\frac{C_r\,V_r}{C_1\,V_1}\right)^2 - 1$$

$$R^2 = \frac{X^2}{\left(\frac{C_r\,V_r}{C_1\,V_1}\right)^2 - 1}$$

$$R = \frac{C_1\,V_1}{\sqrt{(C_r\,V_r)^2 - (C_1\,V_1)^2}}\,|X|.$$

Now $|X| = \omega L \sim \dfrac{1}{\omega C_1}$. When the circuit is tuned to the wavemeter frequency the reactance is zero, i.e.

$$\omega L = \frac{1}{\omega C_r}$$

Therefore

$$|X| = \frac{1}{\omega C_r} \sim \frac{1}{\omega C_1}$$

$$= \frac{1}{\omega C_r}\left(1 \sim \frac{C_r}{C_1}\right)$$

and

$$R = \frac{C_1 V_1}{\sqrt{C_r^2 V_r^2 - C_1^2 V_1^2}} \times \frac{1}{\omega C_r}\left(1 \sim \frac{C_r}{C_1}\right)$$

$$= \frac{V_1}{\sqrt{\left\{\frac{C_r}{C_1}\right\}^2 V_r^2 - V_1^2}} \times \frac{1}{\omega C_r}\left(1 \sim \frac{C_r}{C_1}\right).$$

40. This method is not very suitable for extempore measurements, because since R is generally only of the order of $\cdot 01 \times \frac{1}{\omega C}$, either $\frac{V_1}{\sqrt{\left(\frac{C_r}{C_1}\right)^2 V_r^2 - V_1^2}}$ or $1 \sim \frac{C_r}{C_1}$ must be quite small. If the former is small; the voltage V_1 must be read on the cramped portion of the voltmeter scale, while if $\frac{V_1}{\sqrt{\left(\frac{C_r}{C_1}\right)^2 V_r^2 - V_1}}$ approaches unity, $1 \sim \frac{C_r}{C_1}$ will be of the order of about ·01, i.e. the change of capacitance only about one per cent. This is near the limit of accuracy of an ordinary commercial variable condenser. The difficulty can be overcome if in addition to the standard variable two standard fixed condensers are available. The capacitance (C_p) of one of these should be of the same order as that of the variable condenser at 90° and that of the other (C_s) about one-tenth of this value. These are arranged as in fig. 13, from which it is seen that the total capacitance is $C_p + \frac{C_v\ C_s}{C_v + C_s}$. The total capacitance range is then from a little over C_p, when C_v is at its minimum, to a value approaching $C_p + C_s$ when C_v is at its maximum, i.e. the capacitance changes by rather less than the value C_s as the variable condenser is swung over its whole range. The complete condenser assembly is preferably calibrated in situ by means of a good capacitance bridge.

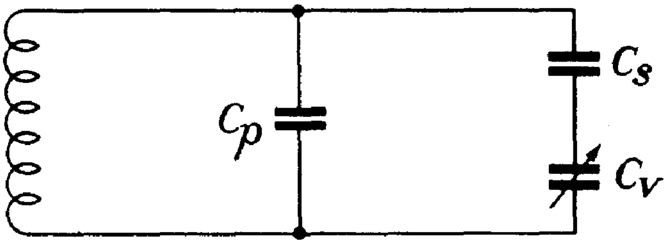


FIG. 13, CHAP. XIII.—Method of obtaining small range of frequency variation.

Capacitance bridge

41. (i) The principle of the Wheatstone bridge may be applied to the measurement of capacitance, provided that a standard condenser is available. The principle of the method is shown in fig. 14a in which R_1 and R_2 are two resistances of exactly equal properties, i.e. their resistances, inductances and self-capacitances are identical. The condenser under test is C_t, while C_s is a calibrated variable condenser. The correctness of balance is indicated by the absence of sound in the telephone receivers, which take the place of the galvanometer in the ordinary wheatstone bridge circuit, while instead of a steady E.M.F. from a battery, audio-frequency alternating E.M.F. is applied to opposite corners of the bridge. From ordinary circuit theory it is easily seen that when the capacitance of the calibrated condenser C_s is equal to that of the condenser C_t, the currents in the two parallel paths, i.e. R_1, C_s and R_2 C_t are equal, and the points X and Y at equal potential, hence no current will flow between X and Y and no sound will be heard in the telephones. When C_s is not equal to C_t however, this is not the case.

(ii) In a commercial form of this instrument, the alternating E.M.F. is produced by means of a small high-note buzzer of the Ericsson type, while the two ratio arms of the bridge are formed by the two halves of a differential condenser, and the instrument is given two ranges by the

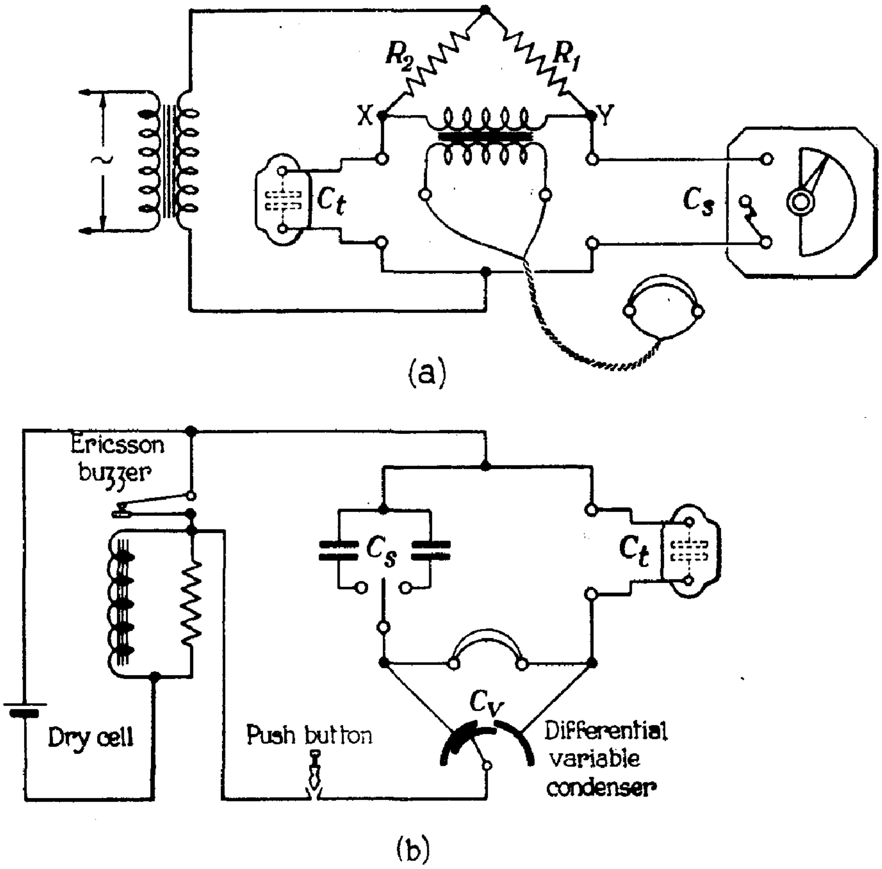


FIG. 14, CHAP. XIII.—Capacitance bridge.

adoption of two alternative fixed condensers in the arm opposite to that containing the condenser under test (fig. 14b). By this means a very wide range of capacitance can be covered in a single sweep of the differential condenser. The latter may be provided with two direct-reading scales of capacitance, and the value of C_t is read from the one corresponding with the particular standard condenser which is switched in for the purposes of the measurement.

Measurement of depth of modulation

42. Instruments used for determining, approximately, the depth of modulation of an R/T transmitter are known as modulation indicators. The principle of the method is shown in fig. 15. Here $L_1 C_1$ is a circuit tuned to the radiated frequency and loosely coupled to the aerial circuit of the transmitter, so that the condenser P.D. is of the order of 10 volts or more ; the greater the amplitude the more accurate the result will be. The alternating voltage across the condenser is rectified by the diode D_1, a reservoir condenser and load resistance C_2, R_2, being fitted as usual ; the values of C_2 and R_2 are chosen in such a way that C_2 can be regarded as a short circuit for the radio-frequency current and of infinitely high reactance for an audio-frequency current while R_2 is so chosen that the time constant $C_2 R_2$ is of the order of 5. Suppose the transmitter to be sinusoidally modulated, so that the envelope of the condenser P.D. has the form of fig. 15b and f is the modulation frequency. The maximum value P and minimum value Q of the envelope can be measured by means of the diode D_2, the microammeter M and the battery E together with the potentiometer R_3.

43. To measure the maximum voltage P it is only necessary to put the switch arm in the position marked P (fig. 15a) and vary the adjustment of the potentiometer R_3 until the current

through the microammeter is zero. The reading of the direct current voltmeter V then gives the voltage *P* (fig. 15b). The change-over switch is then moved to the position Q and the measurement is done in exactly the same way, the reading of the voltmeter V now giving the minimum voltage *Q* (fig. 15b). When the microphone of the transmitter is quiescent the two readings of the voltmeter should be the same for both positions P and Q of the switch. Telephones are fitted in series with the microammeter and it will be observed that these telephones are not absolutely silent at the moment when, by means of the potentiometer R_3, the microammeter reading is brought to zero, because the diode passes some audio-frequency current owing to its capacitance. As soon as the micro-ammeter begins to show a current, a peculiar crackling noise will be heard in the telephones owing to peaks of the modulation being passed by the diode D_2. The moment when the microammeter begins to pass the slightest current can be recognised by the change in the characteristic sound in the telephone, so that in practice the microammeter can be dispensed with.

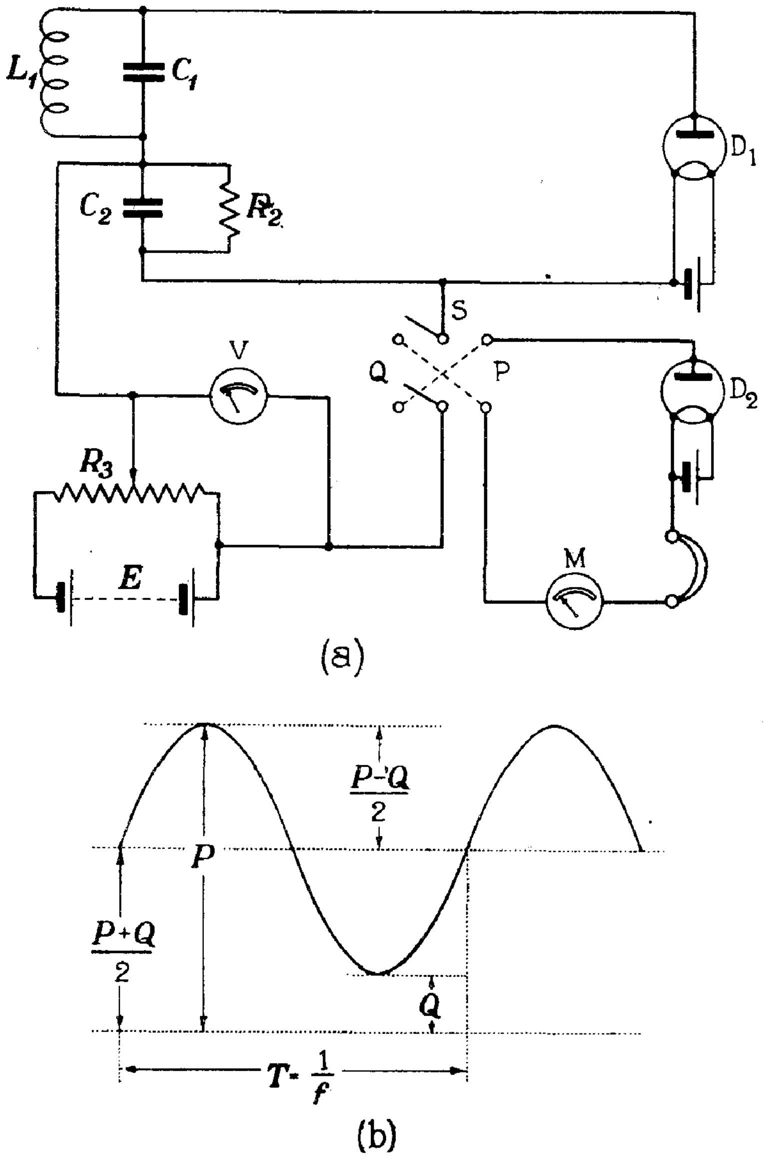


FIG. 15, CHAP. XIII.—Principle of modulation indicator.

44. Having obtained the maximum value P and minimum value Q from the voltmeter V, the depth of modulation K may be determined from the formula

$$K = \frac{P - Q}{P + Q}$$

Many modifications to this method have been made with the object of reducing the amount of manipulation required, but the advantage of the scheme outlined above is that it does not depend upon a prior calibration. If desired, the coil L_1 may be coupled to a radio-frequency amplifier and the measurement performed upon the transmission of a distant station, provided the gain is sufficient to give the required P.D., i.e. not less than 10 volts.

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