OPERATING INSTRUCTIONS

TYPE 667-A

INDUCTANCE BRIDGE

Serial No. 418

667-A

GENERAL RADIO COMPANY

410-I

OPERATING INSTRUCTIONS

TYPE 667-A

INDUCTANCE BRIDGE

Form 410-I
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GENERAL RADIO COMPANY
WEST CONCORD, MASSACHUSETTS, USA

SPECIFICATIONS

INDUCTANCE RANGE:	0.1 μh to 1 h; can be extended by Type 1482 Standard Inductors used as external standards. With internal standard, the bridge will balance for storage factors from 0.06 to infinity at 1 kc.
ACCURACY:	Inductance, $\pm$(0.2% + 0.1 μh). Capacitance across UNKNOWN terminals is about 60 $\mu\mu$f. Specific value is given for each bridge. This capacitance will increase the measured value of large inductors fractionally by ω^2LC. At 1 kc and 1 h the increase is about 0.24%. By direct substitution, two nearly equal external inductors can be compared to $\pm$0.02%.
FREQUENCY RANGE:	All calibration adjustments are made at 1 kc. The bridge can be used from 60 cps to 10 kc, but errors resulting from stray capacitance increase with frequency. When large inductances are measured with external standards, the frequency should be lowered to avoid resonance effects.
STANDARDS:	The standard inductor is a 1-mh toroid wound on a ceramic form. Resistance balance is made by resistors having small residual inductances.
MOUNTING:	Shielded walnut cabinet.
ACCESSORIES REQUIRED:	Oscillator, amplifier, and earphones or visual null detector. Refer to paragraph 1.3.
ACCESSORIES SUPPLIED:	Two Type 274-NCO Shielded Connectors.
DIMENSIONS:	Length 17½ in., width 16 in., height 9½ in., over-all.
WEIGHT:	33 lb.

NOTE

This manual was prepared to accompany the Type 667-A Inductance Bridge, Serial No. 418 , specific data for which are given in:

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TYPE 667-A INDUCTANCE BRIDGE

Section 1
INTRODUCTION

NOTE: For a list of all symbols and equations used in this manual, refer to Appendix on page 14.

1.1 PURPOSE. The Type 667-A Inductance Bridge (Figure 1) is designed primarily for the accurate measurement of the series inductance of small coils having low storage factors, Q, at audio frequencies. Since it can be used to measure inductances up to 1 henry, the Type 667-A constitutes an excellent general-purpose inductance bridge. When connected as a Campbell mutual-inductance bridge, it can be used to measure mutual inductance in terms of the internal standard. Terminals are provided so that the bridge can be connected as a series resonance bridge for accurate measurements of a-c resistance. When the Type 667-A is arranged as a Wheatstone bridge, d-c resistance can be determined by means of a battery and galvanometer used in place of the usual a-c generator and detector.

1.2 DESCRIPTION.

1.2.1 GENERAL. The circuit of the Type 667-A Inductance Bridge is basically the simple impedance bridge circuit shown in Figure 2, where the balance equations in terms of the unknown impedance ($Z_X = R_X + j\omega L_X$) are:

$$L_X = L_S \frac{R_B}{R_A} \qquad (1)$$

$$R_X = (R_S + R_{LS}) \frac{R_B}{R_A} - R_P \qquad (2)$$

For a given value of the standard inductor L_S, the controls of resistors R_A and R_B can be calibrated to be direct-reading in terms of the unknown inductance, L_X. If the standard inductor, L_S, could be made to have zero resistance, the variable resistor R_S in series with it would be enough to balance the resistive component, R_X, of the unknown inductor. Because the standard inductor is an air-core toroid, its resistance is so large that it is frequently necessary to provide a variable resistor, R_P, in series with the unknown inductor to obtain a balance.

The design of the Type 667-A Inductance Bridge overcomes two objectionable features of the simple bridge circuit described above. In equations (1) and (2) above, for instance, the two conditions of balance are not independent. Thus the partial balance point is not unique, and true balance can be recognized only after an alternate series of balances, each yielding a progressively reduced minimum. In other words, the bridge circuit of Figure 2 inherently possesses a "sliding zero" in its balance. In the Type 667-A Bridge a small variable inductor, L_P (see Figure 3), is placed in series with the unknown inductor and is adjusted to obtain a final independent balance. Equation (1) then becomes:

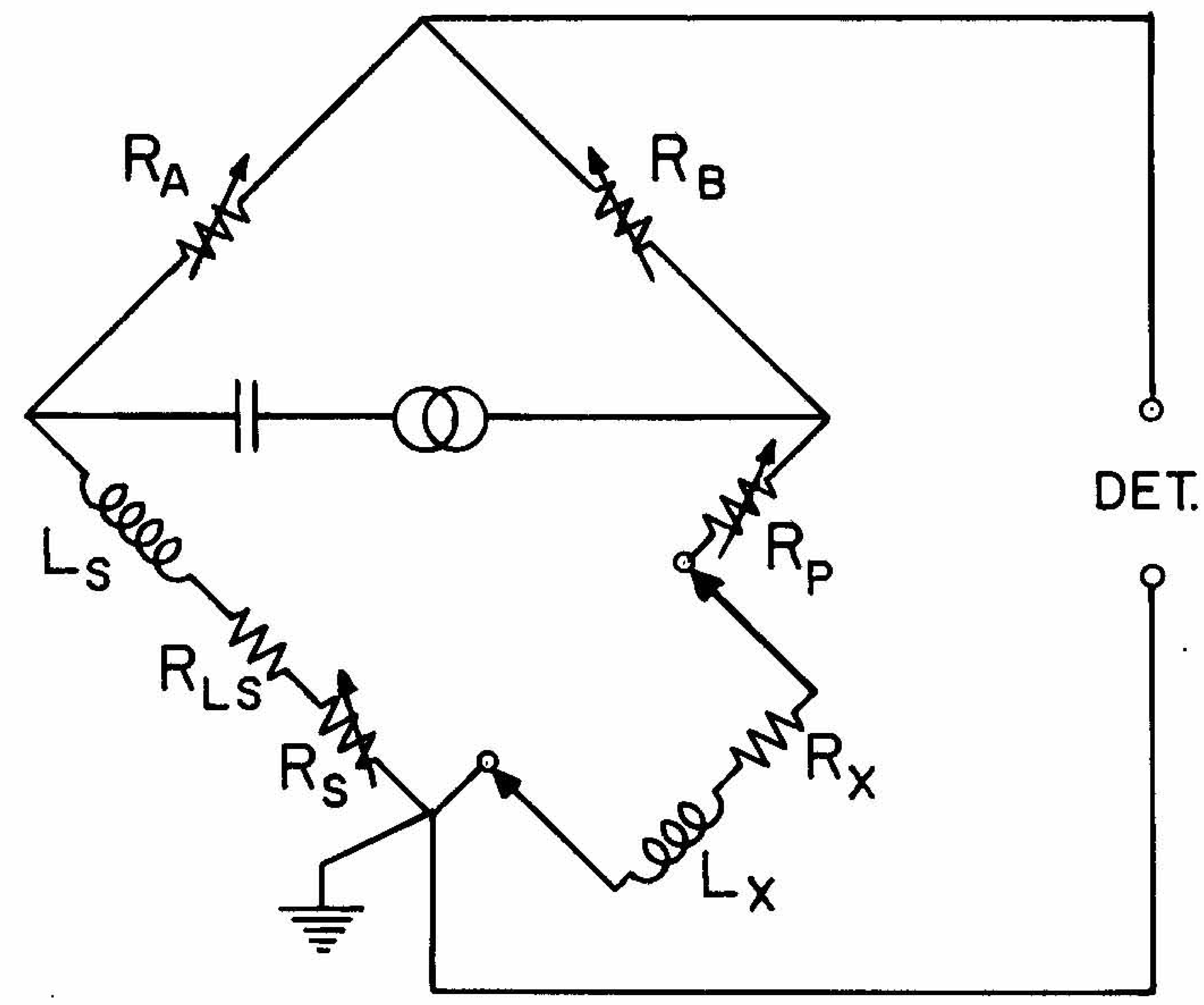

Figure 2. Simple Impedance Bridge Circuit for Measuring Inductance.

$$L_X = L_S \frac{R_B}{R_A} - L_P \qquad (3)$$

and the sliding zero vanishes, since the value of the control L_P does not appear in equation (2). This equation must be modified to include the resistance, R_{LP}, of the variable inductor:

$$R_X = (R_S + R_{LS}) \frac{R_B}{R_A} - (R_P + R_{LP}) \qquad (4)$$

The other serious difficulty encountered in the simple circuit of Figure 2 arises when conventional variable resistors or decade resistors are used for the resistance balance. The residual inductance associated with such resistors varies with setting. Errors are thus introduced in the measurement of small inductances, and the sliding zero is accentuated, since an adjustment of R_S or R_P changes the inductance of the respective arms also. In the Type 667-A, constant-inductance decades of resistance are used for the variable R_S. These decades are so arranged that, as a resistance element is switched out of circuit, a copper winding of the same inductance and negligible resistance is inserted in its place. The residual inductance thus remains constant within 0.1 microhenry.

1.2.2 CONTROLS. The functions of the controls on the front panel of the bridge are as follows:

a. In the upper left-hand portion of the panel, below the engraving R IN S, are three controls labeled TENS, UNITS, and TENTHS. These controls vary the resistance R_S in series with the standard inductor, L_S. The values engraved on the panel and dial give, in ohms, the resistance of R_S.

b. The MULTIPLIER FOR MICROHENRY SWITCHES control in the lower left-hand corner determines the value of the resistance R_A. Because of the inverse relationship between L_X and R_A, the actual resistance must vary inversely with the setting in order to obtain the direct-reading feature. The values of R_A for the various settings are:

MULTIPLIER setting	R_A in ohms
1	1000
10	100
100	10
1000	1

The MULTIPLIER FOR MICROHENRY SWITCHES control is referred to in this manual as the MULTIPLIER control.

c. The main group of four decade switches in the center of the panel, labeled MICROHENRYS, controls the major part of resistance R_B. The readings of these switches (engraved HUNDREDS, TENS, UNITS, TENTHS) multiplied by the MULTIPLIER control setting, plus the microhenry reading on the MICROHENRYS dial, equals the unknown inductance. The MICROHENRYS reading is also the resistance, in ohms, of the variable resistor R_B.

d. The two controls on the right, below the nameplate, provide a discontinuous variation of R_P. The engraved values are direct values of the resistance inserted in series with the unknown, R IN X.

e. The MICROHENRYS dial, at the lower right-hand corner, controls the variable inductor, L_P, in series with the UNKNOWN terminals. The dial calibration gives directly the value of inductance removed from this circuit.

f. Under the snap button above the DETECTOR terminals is a switch (K in Figure 3) that can be used to short out the resistors R_{BO}. This is a contact made or broken by the rotation of a machine screw. The resistors R_{BO} compensate for the maximum inductance of the variable inductor ($L_{P\,max}$), and for the residual inductance of the resistance elements R_P.

1.2.3 CONNECTIONS. Pairs of jack-top binding posts are provided for the connection of GENERATOR, DETECTOR, and UNKNOWN. The binding post marked D is for connection to one of the vertices of the bridge circuit (see Figure 3), and is useful when the Type 667-A is used as a resonance bridge or for d-c measurements (refer to paragraphs 3.9 and 3.10). Binding posts marked STANDARDS provide the option of using either the internal toroidal inductor or an external standard.

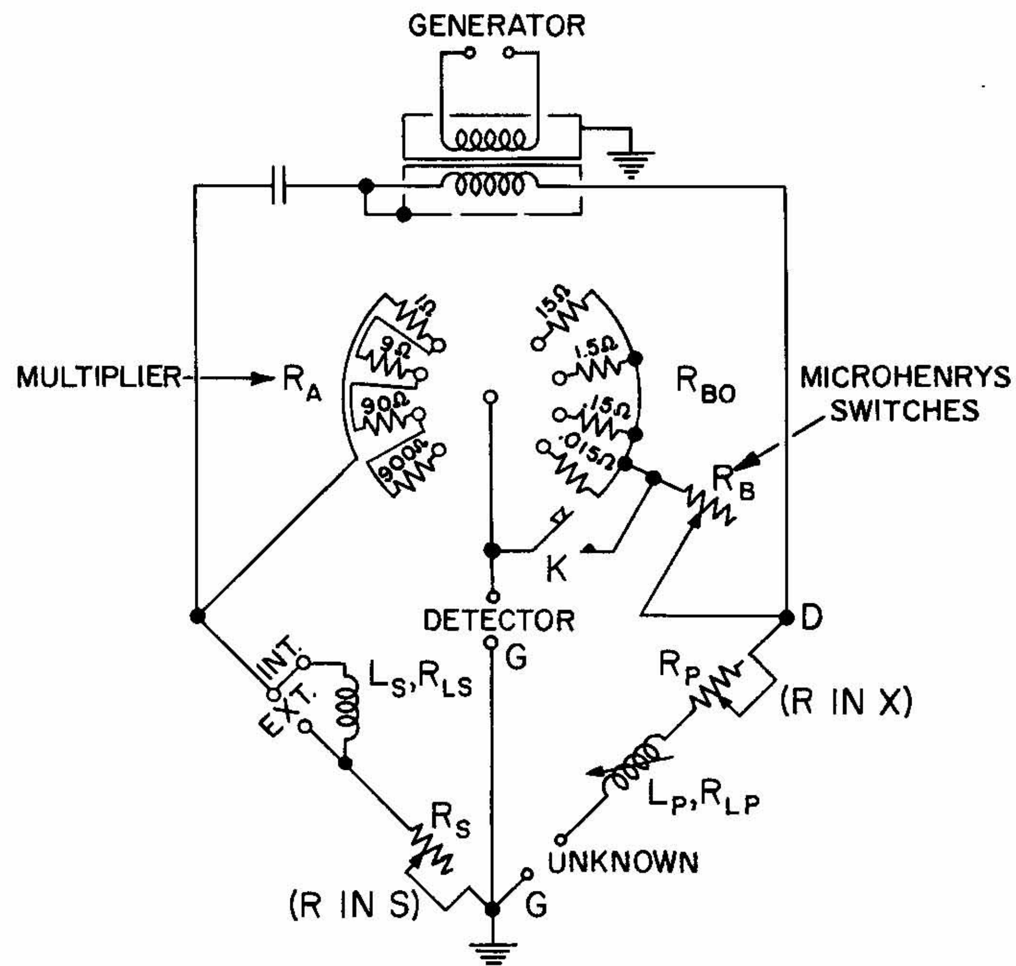

Figure 3. Elementary Diagram of Type 667-A Inductance Bridge.

1.3 ACCESSORIES.

1.3.1 GENERATOR. Almost any audio-frequency generator may be used as a voltage source. If a 60-cycle power line is used, a suitable isolation transformer should be interposed. Recommended oscillators are:

Type 723 Vacuum-Tube Fork
Type 1210 Unit R-C Oscillator
Type 1214-A, -D, -E Unit Oscillators
Type 1301 Low-Distortion Oscillator
Type 1302 Oscillator
Type 1304 Beat-Frequency Oscillator

1.3.2 DETECTOR. Telephones or a visual indicating meter may be used as a null-balance detector in conjunction with any sensitive amplifier with gain control. At 1 kc, telephones are more sensitive than most available meters, while at low or high audio frequencies the meter is likely to be more sensitive. For the measurement of inductors with ferromagnetic cores, a selective detector tuned to the generator frequency is strongly recommended.

1.3.3 OTHER ACCESSORIES. The following table lists those accessories recommended for use with the Type 667-A Inductance Bridge.

External Inductance Standards

Type 1482 Standard Inductors available in the following values:

100, 200, and 500 microhenrys; 1, 2, 5, 10, 20, 50, 100, 200, and 500 millihenrys; and 1, 2, 5, and 10 henrys.

Null Detectors

Type 1212 Unit Null Detector
Type 1231 Amplifier and Null Detector
Type 1951 Filters (for use with Type 1212)

Harmonic Suppressors

Type 1231-P2, -P3, -P5 Tuned Circuit
Type 830 Wave Filters

Variable Capacitor (for resonance bridge methods)

Type 1420 Variable Air Capacitors
Type 219 Decade Capacitors
Type 722 Precision Capacitors

Vacuum-Tube Voltmeters (for iron-core inductors)

Type 1800 Vacuum-Tube Voltmeter
Type 1803 Vacuum-Tube Voltmeter

Section 2
PRINCIPLES OF OPERATION

2.1 THE STANDARD ARM. The total inductance in the standard arm includes not only the standard inductor L_S, but the inductance of the constant-inductance resistor R_S. The latter inductance and the inductance of the circuit wiring total about 1 microhenry. The standard inductance is a 1-millihenry toroid, adjusted to make the total inductance in the standard arm precisely 1.000 millihenry.

The resistor R_S (R IN S) consists of a 0.1- to 1-ohm compensated slide wire (Type 877-400), a 1-ohm-per-step decade (Type 668-B), and a 10-ohm-per-step decade (Type 668-C). As previously noted, these units are constructed so that their total inductance is constant with setting within 0.1 microhenry.

Included in the standard arm are three terminals, which permit: (1) use of an external standard, (2) use of the internal standard, and (3) elimination of the standard inductor for resonance or Wheatstone bridge measurements.

2.2 THE UNKNOWN ARM. Included in the unknown arm are the variable inductor L_P (MICROHENRYS dial) and the variable resistor R_P (R IN X), as well as the UNKNOWN terminals. The resistor R_P consists of two units which cover the range from zero to 10 kilohms in 14 steps, with approximately logarithmic resistance increments. The low-resistance unit, zero to 100 ohms, is compensated to give constant inductance in the manner of R_S. The high-resistance unit, zero to 10 kilohms, is not compensated, and actually introduces a small capacitive reactance. The constant inductance of R_P is taken into account in the calibration of the variable inductor L_P. The uncompensated unit of R_P will be used only when the storage factor of the unknown inductor is appreciably higher than the storage factor of the standard inductor. Since this can usually occur only when the unknown inductance is large, the fractional error due to the capacitive reactance of the uncompensated unit will be negligible.

2.3 RESIDUAL CAPACITANCE ACROSS UNKNOWN INDUCTOR. The input transformer, the variable resistors R_P and R_B, and the variable inductor L_P combine to place a certain amount of residual capacitance, C_T, internally across the UNKNOWN terminals. For this particular bridge, Serial No. 418, the value of C_T has been measured to be 60.1 $\mu\mu$f. This stray capacitance loads the unknown inductor when attached for measurement, and reduces the direct-reading accuracy of the bridge on the two highest MULTIPLIER settings (100 and 1000). The fractional error, ρ, introduced by this capacitance varies as the square of the frequency in radians per second, as the first power of the unknown inductance in henrys, and as the first power of C_T in farads according to the approximation:

$$\rho = \frac{\Delta L_X}{L_X} \doteqdot \omega^2 L_X C_T \qquad (5)$$

Accordingly, for this particular bridge, the fractional error at 1 kc for an L_X of 1 henry would be .237 %. The true value of the unknown, unloaded by C_T, can thus be computed:

$$\text{True } L_X = (1 - \rho)\ (L_X \text{ as measured}) \qquad (6)$$

This correction to L_X will be significant only under conditions in which lead inductance to the unknown is negligible. Nontwisted parallel leads should be used to avoid increasing C_T beyond the value specified above.

2.4 THE B (RATIO) ARM. The resistance R_B (MICROHENRYS switches) consists of four decade resistance units of 0.1, 1, 10, and 100 ohms per step. The resistor R_{BO} (Figure 3) compensates for the internal inductance of the unknown arm when the dial of L_P is set to zero. The complete equation for inductance balance is:

$$L_X = \frac{R_B}{R_A} L_S + \frac{R_{BO}}{R_A} L_S - L_{P\,max} + L_D \qquad (7)$$

where $L_{P\,max}$ is the maximum inductance of the P arm (exclusive of L_X). It corresponds to the zero reading of the calibrated MICROHENRYS dial. L_D is the actual reading of the MICROHENRYS dial. The quantity $L_{P\,max}$ is made equal to $\frac{R_{BO}}{R_A} L_S$ in locating the zero point on the MICROHENRYS dial. The resistance R_{BO} has a value of 15 ohms with the MULTIPLIER at 1 and has values of 1.5 ohms, 0.15 ohm, and 0.015 ohm at the other switch settings. The panel controls for R_A and R_B are engraved in such a manner that the quantity $\frac{R_B}{R_A} L_S$ is directly in microhenrys. L_D is indicated directly in microhenrys on the MICROHENRYS dial. Therefore the inductance L_X between the UNKNOWN terminals is given in terms of the bridge controls by

$$L_X = AB + L_D \text{ microhenrys} \qquad (8)$$

where A is a factor indicated by the MULTIPLIER setting, B the composite reading of the four MICROHENRYS switches, and L_D the MICROHENRYS dial reading. Note that the value of L_D is not multiplied by the factor A.

Equation (8) is the basic working equation of this bridge. It gives the inductance of the unknown, subject to possible corrections (refer to paragraphs 2.3 and 3.5.2).

2.5 THE A (RATIO) ARM. The resistance R_A has a value of 1000 ohms with the MULTIPLIER control at 1, and values of 100 ohms, 10 ohms, and 1 ohm at the other switch settings.

In some bridges a compensating capacitor, C_C, is connected across the 1-ohm unit of the A arm to reduce small errors produced by certain bridge residuals. The existence and value of C_C are of no concern to the user.

2.6 INPUT TRANSFORMER. A Type 578-A Shielded Transformer isolates the generator from the bridge circuit, reducing the voltage applied to the bridge network to 0.25 times that supplied at the bridge GENERATOR terminals. The terminal capacitance and the direct capacitance of this transformer are small, about 30 $\mu\mu$f and 0.3 $\mu\mu$f respectively. The bridge is therefore independent of the ground capacitances at the GENERATOR terminals. The bridge is grounded at the junction of the two inductance arms, and therefore the transformer terminal capacitances appear across these inductances where the smallest errors are introduced.

The frequency range of the input transformer covers the audio frequencies from 50 cps to 10 kc. The transformer is conductively isolated from the bridge network by a 0.5-μf paper capacitor so that the Type 667-A Bridge can be used for d-c measurements of resistance.

Section 3
OPERATING PROCEDURE

3.1 INSTALLATION. Using a Type 274 Shielded Connector, connect the audio-frequency oscillator to the GENERATOR terminals, applying the shield to the low or ground terminal of the oscillator. Connection at the bridge terminals is optional.

Connect the null detector input to the bridge DETECTOR terminals with the other Type 274 connector, applying the shield to the grounded post on the bridge and to the grounded or low detector input. It may be desirable to apply a good ground (earthed) connection to the grounded UNKNOWN terminal.

3.2 MAXIMUM SAFE VOLTAGE AT GENERATOR TERMINALS. The following table indicates the maximum voltage that can safely be applied to the GENERATOR terminals, with internal and external standards:

TABLE 1
MAXIMUM SAFE VOLTAGE AT GENERATOR TERMINALS

Unknown	Internal Standard		External Standard[1]	
	Limited By	Volts rms	Limited By	Volts rms
1 h	Ratio arm B	320[2]		
100 mh	Ratio arm B	320[2]		
10 mh	Int std (2 watts)	152[2]	Ratio arm B	320[2]
1 mh	Int std (2 watts)	28	Transformer	90
0.1 mh	Int std (2 watts)	15	Ratio arm A	101
0.01 mh	Int std (2 watts)	14	Ratio arm A	93
0.001 mh	Int std (2 watts)	14	Ratio arm A	92

[1]With enough power-handling capacity so that only the bridge elements limit the volts.

[2]At 1000 cps. At lower frequencies the transformer is the limiting factor and these voltages should be reduced proportionally to 115 volts at 50 cps.

3.3 PROPER USE OF R IN X AND R IN S CONTROLS. To obtain maximum accuracy and to minimize the sliding zero in balancing, the Q of the entire P arm should be as large as possible, which means that R_P (R IN X) should have the lowest available value that will permit the bridge to be balanced. The range of R IN X extends to 10,100 ohms but, in the interest of economy, this need not be a continuous adjustment, since R IN S is continuously adjustable. Thus the two R IN X controls are designed to give approximately logarithmic increments of R_P. In making a measurement, proceed as follows:

a. Set both R IN X controls to zero.

b. Attempt to balance the bridge using R IN S as the resistive control.

c. If the required value of R IN S indicated in step b is less than zero, increase R IN X by the smallest available amount and repeat step b.

d. Proceed in this manner to find the smallest available value of R IN X that will permit balance with some value of R IN S greater than zero.

An alternate procedure would be to balance the bridge with an arbitrary value of R IN X, and then to determine how much R IN X (and R IN S) can be reduced and still permit balance.

3.4 BRIDGE BALANCE WITH A SLIDING ZERO. When the unknown inductance is greater than about 10 microhenrys it becomes necessary to use the MICROHENRYS switches for at least the preliminary balance. In this instance a sliding zero will be encountered, which will become more accentuated as the storage factor of the entire P arm decreases. This unfortunately is a feature inherent in the Type 667-A as well as in many other inductance bridges.

There can be only one true and complete null balance; i.e. there is only one correct setting for each of the two balancing controls that will give zero detector voltage, and for which the balance equations are valid. To establish this true balance in the presence of a sliding zero requires a little patience and experience on the part of the user. The recommended procedure is as follows:

a. Adjust the MICROHENRYS switches to produce the lowest minimum response of the detector. This may be a broad and rather unsatisfactory operation. Make sure that, with the bridge badly out of balance, the null detector is not overloaded.

b. Obtain a reduced response on the null detector by adjustment of the R IN S controls. This should yield a more pronounced minimum, which may still be broad.

c. Make a second adjustment of the MICROHENRYS switches to obtain a still lower and sharper minimum response.

d. Using the R IN X controls, further improve the balance.

Proceed with these alternate adjustments until the final (true) balance is obtained. Increase the sensitivity of the detector, without overloading, when feasible. Do not try to adjust both controls simultaneously, or you may find yourself running in circles.

With a little skill you can expedite this procedure by "overshooting" each control adjustment slightly in anticipation of the sliding zero. When the preliminary adjustments have been accomplished, the final precise balance may be obtained with the R IN S and MICROHENRYS dial controls with no sliding zero.

An alternative procedure would be to insert a calibrated variable inductor (Type 107 recommended) externally in series with the unknown, and to use it instead of the MICROHENRYS switches for balancing. The inductance of the unknown would then be L_X given by Equation (8) minus the final indication of the Type 107 or other inductor.

3.5 DIRECT OPERATION WITH INTERNAL STANDARD.

3.5.1 GENERAL. With the link at the STANDARDS terminals connected from the INTernal post to the lower of the two EXTernal posts (Figure 1) and with switch K (under the snap button) open (fully counterclockwise), the bridge is ready for direct-reading measurements of inductance with the internal standard.

The inductor to be measured must be connected to the UNKNOWN terminals, but away from any metal objects (including the copper-lined cabinet of the bridge) that might affect its inductance. If one extremity of the unknown has a predominant capacitance to ground, connect it to the ground terminal. Leads (preferably loosely twisted) must then be used, and, for accurate measurements of small inductances, the inductance of these leads must be determined.

3.5.2 DETERMINATION OF LEAD INDUCTANCE. To determine the lead inductance, L_O, proceed as follows:

a. Short-circuit the unknown inductor at its own terminals, set the MICROHENRYS and R IN X switches to 0, set the MULTIPLIER switch to the value to be used when the unknown inductor is in circuit, and balance by means of the MICROHENRYS dial and R IN S controls alone. Note the inductance L_O, which is indicated directly in microhenrys on the MICROHENRYS dial. (The MICROHENRYS dial reading is never multiplied by the MULTIPLIER setting.)

b. Remove the short circuit across the unknown inductor and rebalance the bridge by means of the MICROHENRYS decade switches and by means of the R IN S and R IN X variable resistors. (Refer to paragraph 3.3.)

The initial balance procedure for L_O described above must be repeated if the MULTIPLIER setting is changed in order to utilize as many of the MICROHENRYS switches as possible. As the final balance point is approached and falls within the range of the variable inductor, it can be quickly determined by adjustment of the MICROHENRYS dial. Equation (8) is then modified to give the unknown inductance:

$$L_X = AB + L_D - L_O \text{ microhenrys} \qquad (9)$$

where A is the MULTIPLIER setting, B is the composite setting of the MICROHENRYS switches, L_D is the setting of the MICROHENRYS dial for final balance, and L_O is the setting of the MICROHENRYS dial for initial balance. Note that all quantities are read directly from dial and panel calibrations, and no reference need be made to actual circuit values within the bridge.

3.5.3 ALTERNATE METHOD OF COMPENSATING FOR LEAD INDUCTANCE. When several inductors of less than 1 millihenry are to be measured with the same leads used for each, the lead inductance, L_O, may be set up permanently on the UNITS and TENTHS decades of the MICROHENRYS switches, with the MICROHENRYS dial set to zero for the initial balance and the MULTIPLIER switch set at 1. In making this initial balance, set the MICROHENRYS switches approximately and make the balance by adjusting the MICROHENRYS dial. Then correct the switch settings to bring the dial to zero, and check by rebalancing. When the inductor under test is placed in circuit, the unknown inductance can then be balanced directly by means of the TENS and HUNDREDS decades of the MICROHENRYS switches and the MICROHENRYS dial, without disturbing the UNITS and TENTHS decades. The unknown inductance is then expressed:

$$L_X = B_{partial} + L_D \text{ microhenrys} \qquad (10)$$

where $B_{partial}$ is the reading of the TENS and HUNDREDS decades and L_D is the reading of the MICROHENRYS dial at final balance.

3.6 DIRECT OPERATION WITH EXTERNAL STANDARD.

An external inductance standard of known value is recommended for best results when the unknown inductance exceeds 0.1 henry, and must be used when the unknown exceeds 1.1 henrys. To remove the internal toroidal inductance standard from the circuit, open the short-circuiting link at the STANDARDS terminals. The external standard can then be connected to the two STANDARDS terminals marked EXT, with its low extremity connected to the upper of the two terminals. If the standard inductor has an appreciable magnetic field, be careful to keep it away from all metal objects. If a Type 1482 Standard Inductor is used, it may be placed close to the bridge cabinet and connected with short parallel leads. Note that neither extremity of the external standard is grounded to the bridge panel.

Short-circuit the resistors R_{BO} (Figure 3) by turning switch K (under the snap button) fully clockwise to close the switch. The variable inductor (MICROHENRYS dial) must be set to its maximum scale reading, which gives very nearly its actual minimum inductance value (the actual inductance L_P decreases as the dial setting, L_D, is increased). Connect the unknown inductor to the UNKNOWN terminals using parallel leads. Since this unknown inductance is at least 0.1 henry, the minimum inductance of the variable inductor and the inductance of the connecting leads to the unknown can ordinarily be overlooked. Balance the bridge by means of the MICROHENRYS switches, MULTIPLIER, R IN S, and R IN X. (Refer to paragraph 3.3.) If possible, choose a MULTIPLIER setting that will utilize all four MICROHENRYS switches. The unknown inductance, L_X, is given by the data obtained in this single balancing operation:

$$L_X = \frac{AB}{1000} L_S' \text{ henrys} \qquad (11)$$

where L_X is expressed in henrys, A is the MULTIPLIER setting, B is the composite setting of the MICROHENRYS switches, and L_S' is the inductance of the external standard in henrys. The value of L_X from (11) may be subject to a final loading correction by equation (6).

3.7 SUBSTITUTION MEASUREMENTS.

The Type 667-A Bridge is capable of intercomparing three or more nearly equal inductors with a tolerance less than the ±0.2% specified for direct measurements. If one of these is a Type 1482 Standard Inductor, the others may be calibrated in terms of its accurately known value, L_S'. This substitution method eliminates any calibration errors in the components of the A arm, and in most of the B arm, as well as certain residual errors, and increases accuracy about tenfold. The standard and the unknown are introduced successively into the unknown arm of the bridge and two individual balances are made.

a. Close the K switch (turn fully clockwise), set the MULTIPLIER to 1 and the MICROHENRYS dial to its maximum scale reading. Select any one of the unknowns to serve as a reference inductor and connect it in place of the internal toroidal standard as described in paragraph 3.6.

b. Connect the STANDARD inductor to the UNKNOWN terminals and balance the bridge, using the MICROHENRYS switches and R IN S and R IN X controls (refer to paragraph 3.3). The composite reading of the MICROHENRYS switches at balance should be about 1000, and will be known as B_S.

c. Replace the standard with the unknown to be measured. Keep the same R IN X setting and rebalance the bridge to give a new value, B_X, which should also be about 1000.

The value of the unknown, in the same units as L_S', is then expressed:

$$L_X = \frac{B_X}{B_S} L_S' \qquad (12)$$

which does not involve the value of the reference inductor.

To minimize any errors in the calibration of the MICROHENRYS decades, the settings of at least the HUNDREDS and, if possible, the TENS switches should be identical in each of the two balances. For example, a pair of settings might be B_S = 986.5 and B_X = 9X7.3* (= 1007.3, numerically). Do NOT use B_X = X07.3 (also = 1007.3). In this instance, the ratio would be 1.0108 and the unknown would be 1.08% larger than the standard inductor. Since both B_S and B_X are readable to 1 part in 10,000, their ratio may be considered accurate to ±0.02%.

If the two inductors are very closely equal and if one can interpolate between adjacent points on the TENTHS MICROHENRYS switch (giving, for instance,

*Here the symbol X indicates the highest (10) value of the decade.

B_X = 987.68 and B_S = 987.55), the ratio is 1.00013, accurate, theoretically, to ±0.002%.

Such techniques permit highly accurate adjustments of the unknown to some prescribed value, investigations of its temperature coefficient, etc.

3.8 RESISTANCE BALANCE.

3.8.1 GENERAL. The Type 667-A Inductance Bridge is not intended for the simultaneous direct determination of resistance and inductance. The determination of R_X, the series a-c resistance of the unknown, involves equations that are relatively cumbersome, when the bridge is set up for direct inductance measurement. The procedure is detailed below, but it is recommended that, for a-c resistance measurements, the circuit be connected as a resonance bridge (refer to paragraph 3.9).

For accuracy in all resistance measurements, the quantity R_S must be the total resistance of the R_S controls:

$$R_S = \text{Indicated (R IN S)} + r \text{ ohms} \qquad (13)$$

where the small increment, r, is the zero-setting resistance of these controls. For this particular bridge, Serial No. 418, r has been measured to be .315 ohms.

3.8.2 EQUATION FOR RESISTANCE BALANCE USING INTERNAL STANDARD. The expression for the unknown series resistance, R_X, that accompanies equation (9), paragraph 3.5.2, may be derived as follows:

For the initial balance, with the unknown inductor shorted at its terminals, the condition for the resistive component of balance is, in effect, a Wheatstone bridge equation:

$$R_{LP} + R_P = (R_{LS} + R_S)\frac{R_{BO} + R_B}{R_A} \qquad (14)$$

where R_{LP} and R_{LS} are the resistances of the inductors L_P and L_S respectively, and the other symbols are as previously assigned.

With the short circuit removed from the unknown inductor, and the null balance restored by adjustment of R_P, R_S, R_B, and L_P

$$R'_{LP} + R'_P + R_X = (R_{LS} + R'_S)\frac{R_{BO} + R'_B}{R_A} \qquad (15)$$

where the primed quantities refer to the values of the variable elements at the second or final balance.

Combining equations (14) and (15),

$$R_X = \frac{R_{LS}(R'_B - R_B) + (R'_S - R_S)R_{BO} + R'_S R'_B - R_S R_B}{R_A} - (R'_P - R_P) - (R'_{LP} - R_{LP}) \qquad (16)$$

which can be rewritten for convenience as

$$R_X = \frac{A}{1000}\left[R'_S B' + R_{LS}\Delta B - R_S B\right] + 0.015\Delta R_S - \Delta R_P - \Delta R_{LP} \qquad (17)$$

where

$\Delta B = B' - B$ = Change in MICROHENRYS switches reading from final to initial balance.

$\Delta R_S = R'_S - R_S$ = Change in R IN S reading.

$\Delta R_P = R'_P - R_P$ = Change in R IN X reading.

$\Delta R_{LP} = R'_{LP} - R_{LP}$ = Change in resistance of variable inductor.

A = MULTIPLIER setting $= \frac{1000}{R_A}$

0.015 $= \frac{R_{BO}}{R_A}$ for any setting.

An obvious difficulty with equation (17) is that it includes both R_{LS} and ΔR_{LP}, which are not accurately known. Both inductors, being wound of copper wire, have high temperature coefficients of resistance. Also, because of skin effect, their effective resistances at the frequency of measurement differ from their d-c resistances and are interdeterminate functions of frequency. Another less obvious difficulty is the fact that the residual shunt capacitances across R_A and R_B, as well as other residual circuit capacitances, were disregarded in the derivation. These residuals, while having a negligible effect on the inductance measurement, can sometimes produce serious errors in the resistance as calculated from equation (17).

3.9 USE AS A SERIES RESONANCE BRIDGE.

3.9.1 GENERAL. The series resonance bridge is one of the most accurate methods available for measuring the resistance of inductors at audio frequencies. The Type 667-A Inductance Bridge can be easily connected as such a resonance bridge, the only additional equipment required being a variable capacitor capable of tuning the unknown inductor to the frequency of operation.

3.9.2 DETERMINATION OF UNKNOWN RESISTANCE. Turn switch K (under snap button) fully clockwise, short the STANDARD EXT terminals with the link, and connect the unknown inductor in series with a suitable variable capacitor, C, from terminal D to the grounded UNKNOWN terminal (see Figure 4). Recommended capacitors are the General Radio Type 1428 Variable Air Capacitor, Type 219 Decade Capacitor, and Type 722 Precision Capacitor. The R IN X controls and also L_S and L_P are no longer in circuit.

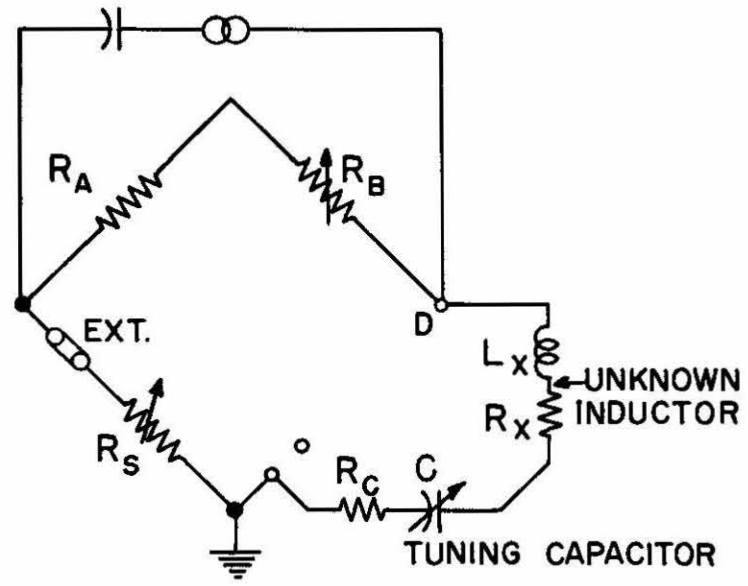

Figure 4. Series Resonance Bridge for Measuring R_X (a-c value) Using External Tuning Capacitor.

The A, B, and standard arms of the bridge now contain resistance only; consequently, for a balance, the unknown arm must be made purely resistive. To do this, resonate L_X with C to establish the relation $\omega^2 L_X C = 1$, and give the unknown arm a zero phase angle.

Balance the bridge by adjusting the variable capacitor to resonance with the unknown inductor, and by adjusting R_S and R_B (R IN S and MICROHENRYS switches, respectively). If possible, choose the MULTIPLIER, R_A, so as to utilize all the R_S and R_B controls. The total resistance R_X and the resistance of the tuning capacitor, R_C, is then given by the Wheatstone equation:

$$R_X + R_C = \frac{R_B}{R_A} R_S \tag{18}$$

to a very high degree of accuracy. Refer to equation (13) for R_S. In terms of the quantities read from the panel, equation (18) becomes the working equation:

$$R_X = \frac{ABR_S}{1000} - R_C \quad \text{ohms} \tag{19}$$

The resistance of the tuning capacitor, R_C, can be computed as the product of its reactance and its dissipation factor, D:

$$R_C = \frac{D}{\omega C} \tag{20}$$

For mica and air capacitors D will be less than 0.0005.

If the distributed capacitance of the unknown inductor is not too large, the value of R_C in equation (19) may prove to be negligible according to the following criteria. The resistance R_X may be expressed as the ratio of the reactance of the unknown inductor to its storage factor, Q:

$$R_X = \frac{\omega L_X}{Q} \tag{21}$$

Hence, at resonance:

$$R_X + R_C = \frac{\omega L_X}{Q} + \frac{D}{\omega C} = \omega L_X \left(\frac{1}{Q} + D\right) \tag{22}$$

showing that R_C can be disregarded in equations (18) and (19), provided that the D of the tuning capacitor is known to be negligible compared with the reciprocal of the Q of the unknown inductor. In this instance the values of C, D, and ω are not required in determining R_X.

3.9.3 DETERMINATION OF UNKNOWN INDUCTANCE. Provided that the natural frequency of the unknown is much higher than the operating frequency, L_X may be computed approximately as:

$$L_X \doteq \frac{1}{\omega^2 C} \quad \text{henrys} \tag{23}$$

when C is in farads.

The quantities C and ω are not generally known very accurately. Moreover, this balance condition is affected appreciably by the residual inductances and stray capacitances of the circuit. Thus it is recommended that inductance measurements be made by the direct methods outlined in paragraph 3.5 or 3.6 rather than by computation from equation (23).

3.10 DIRECT-CURRENT MEASUREMENT OF RESISTANCE. To make direct-current resistance measurements on either an inductor or resistor, proceed as follows:

a. Turn switch K clockwise (closed) and short the STANDARD EXT terminals with the link.

b. Connect a battery* between terminal D and the STANDARD EXT terminals (replacing the external oscillator). See Figure 5.

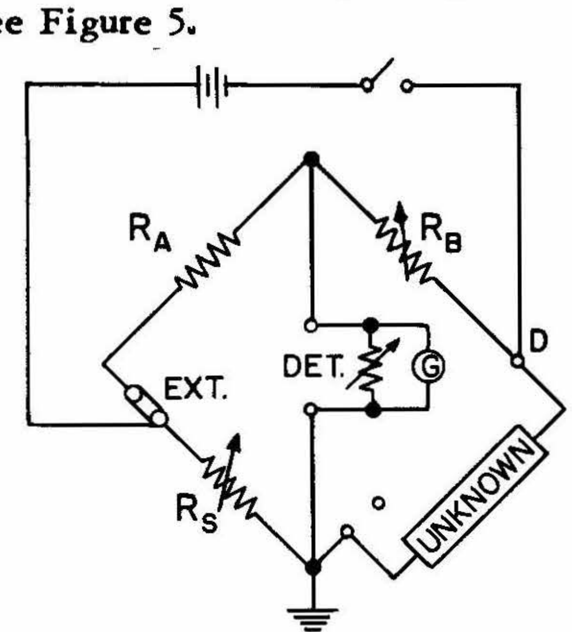

Figure 5. Wheatstone Bridge for Measuring D-C Resistance Using External Battery and Galvanometer.

*Be careful that the current through the bridge arms does not exceed the current ratings of the resistors in the arms. Each resistor is able to dissipate 0.5 watt without excessive temperature rise.

c. Connect a d-c galvanometer and adjustable sensitivity control to the detector terminals, and connect the unknown to be measured between the D terminal and the grounded UNKNOWN terminal.

d. The circuit is now a simple Wheatstone bridge, balanced by the adjustment of R_B and R_S (MICROHENRYS switches and R IN S controls respectively). Choose the MULTIPLIER, R_A, to utilize all of the R_B and R_S controls, if possible. The unknown resistance is expressed as:

$$(R_X)_{DC} = \frac{R_B}{R_A} R_S = \frac{ABR_S}{1000} \text{ ohms} \qquad (24)$$

Refer to equation (13) for R_S.

3.11 RATIO OF A-C TO D-C RESISTANCE.

The methods described in paragraphs 3.9.2 and 3.10 can be applied successively to an inductor to obtain an accurate indication of the ratio of a-c to d-c resistance. If R_A and R IN S are left at the same settings in the two measurements, only R_B will have to be adjusted. Because R_B will be only slightly altered between the two measurements, the ratio of the a-c to d-c resistance of the inductor, i.e. the ratio of the two R_B values, will be known much more accurately than the calibration of the B arm itself, provided the resistance of the tuning capacitor in equation (19) is negligible.

3.12 MEASUREMENT OF MUTUAL INDUCTANCE.

3.12.1 DIRECT MEASUREMENT. When the primary (L_1) and secondary (L_2) windings of a mutual inductor are connected in series, the total self-inductance (L_T) of the pair is:

$$L_T = L_1 + L_2 \pm 2M \qquad (25)$$

where L_1 and L_2 are the individual self-inductances of the windings and M is the mutual inductance between them. Then the coefficient of coupling, K, between the two windings is given by:

$$K = \frac{M}{\sqrt{L_1 L_2}} \qquad (26)$$

The mutual inductance M can then be calculated from the two directly measured self-inductances L_{aid} and L_{opp} obtained with the two windings aiding and opposing (using the plus and minus signs before 2M). Use the procedure outlined in paragraphs 3.5 and 3.6. Then:

$$M = \frac{L_{aid} - L_{opp}}{4} \qquad (27)$$

For a coefficient of coupling near the maximum value of 1, where L_{opp} is very small compared with L_{aid}, the error in determination of M is that of L_{aid} itself. For smaller coupling coefficients this error increases. For instance, when K = 0.1 and $L_1 = L_2$, this error is increased five-fold. The self-inductance measurement can be made directly by the inductance bridge with an error of $\pm(0.2\% + 0.1\ \mu h)$. The increase in the error as the two separate bridge balances approach each other is minimized if the MULTIPLIER is kept fixed and the change in balance is taken up by the minimum changes in the B arm. The error is then that of the change in resistance of the decade MICROHENRYS controls.

3.12.2 CAMPBELL BRIDGE METHOD. Mutual inductances can also be measured by means of the Campbell bridge network, as follows:

a. Make a direct measurement (paragraph 3.5 or 3.6) of one of the windings alone and designate this value L_1.

b. Add the second (unmeasured) winding, L_2, in series with the low input lead to the null detector, thus forming the Campbell bridge shown in Figure 6.

c. Rebalance the bridge and designate the apparent value of this measured unknown as L_1', and the corresponding MULTIPLIER and MICROHENRYS switch settings as A′ and B′. The mutual inductance between the two windings will then be:

$$M = \frac{L_1 - L_1'}{1 + \frac{A'B'}{1000}} \qquad (28)$$

Positive and negative values of M indicate aiding and opposing coupling respectively.

The errors are slightly less than those in paragraph 3.12.1 because, for a given mutual inductance,

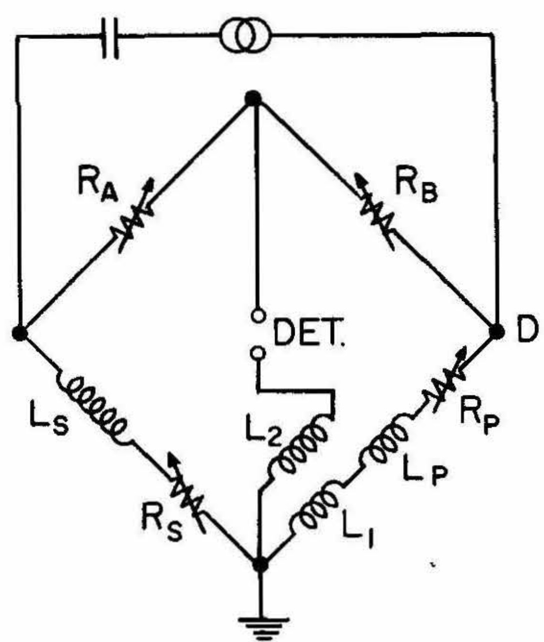

Figure 6. Campbell Bridge Connection for Measurement of Mutual Inductance.

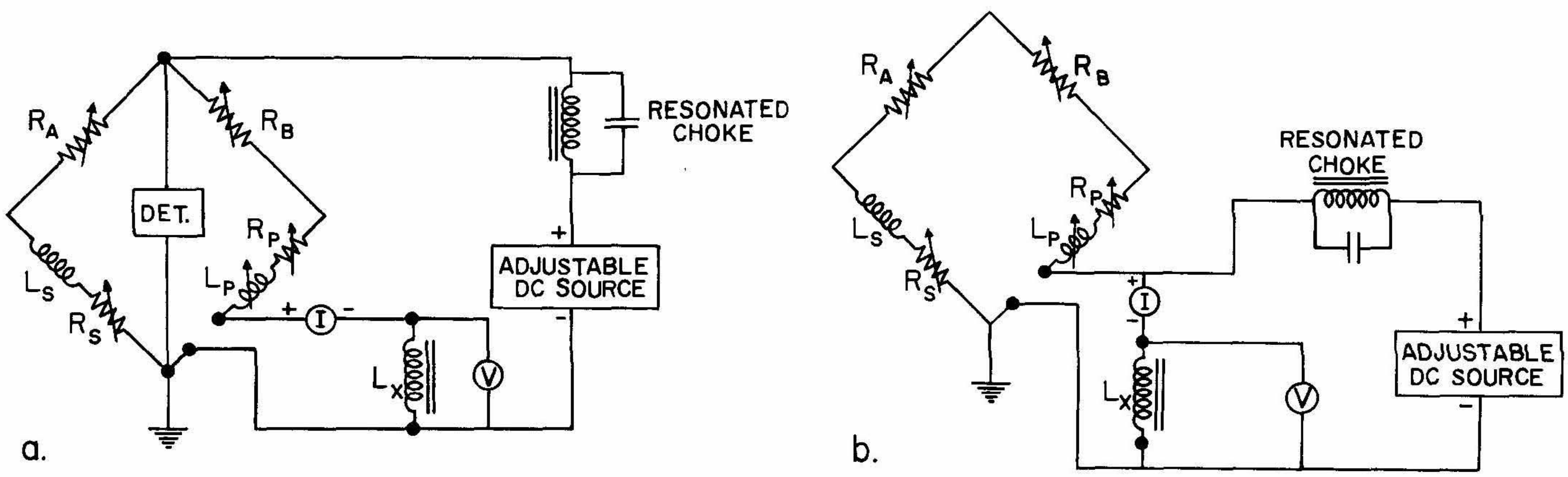

Figure 7. Arrangements for Incremental Inductance Measurements.

the difference between the two bridge settings is reduced by at least a factor of three, and there is a greater chance of keeping both bridge balances within a single decade setting lower than the highest one used.

3.13 IRON-CORE INDUCTORS WITH DC (INCREMENTAL INDUCTANCE). Although not designed for measurements with superimposed direct current, the Type 667-A can be used for measurements of incremental inductance over limited ranges if proper external arrangements are made for d-c feed. Measure the d-c polarizing current through the unknown inductor by placing a suitable d-c ammeter in series with it across the UNKNOWN terminals. The a-c voltage across the unknown inductor must also be measured (refer to paragraph 3.14).

a. One commonly used method of feeding direct current through the unknown is to place an adjustable d-c source across the DETECTOR terminals of the bridge (see Figure 7a). Connect a high-impedance choke in series with the d-c supply to maintain the impedance across the output of the bridge at a reasonably high level. It may also be desirable to place a capacitor in the input lead to the amplifier being used as a detector. Here the choke impedance introduces no error in the measurements, but the R IN X and MICROHENRYS switches must carry the polarizing current.

b. Another method is to connect the adjustable d-c supply, in series with a high-impedance choke, directly across the UNKNOWN terminals (see Figure 7b). Here the impedance of the choke is effectively in parallel with the unknown inductor being measured, but the internal bridge components do not carry the polarizing current in the unknown.*

In either method, the impedance of the choke may be increased greatly if the choke is resonated with a capacitor of appropriate value connected across it. There will then be less difficulty in making the choke impedance high enough to become a negligible factor in the measurement. The limitation then becomes the ability of all four of the bridge arms to carry the direct current passing through them. No simple value can be given, nor can a simple table be devised to state this current limitation. The best guide is the wattage rating of each resistor in the bridge. As stated earlier, resistors in the bridge are capable of dissipating about 0.5 watt without excessive temperature rise.

3.14 GENERAL CONSIDERATIONS.

3.14.1 INDUCTANCE OF IRON-CORE INDUCTORS. It must be understood that a specified L_X value of any inductor having a ferromagnetic (magnetically nonlinear) core is quite meaningless unless the concurrent a-c voltage across it or the alternating current through it is also specified. This is because the effective permeability of the core may vary pronouncedly with the level at which it is energized.

The a-c voltage across the unknown inductor during a direct L_X measurement can be determined with a high-impedance vacuum-tube voltmeter. Unfortunately, this voltage can vary with the adjustment of the balancing controls. If L_X at a specified voltage is desired, means must be provided for monitoring the generator voltage applied to the bridge.

Similarly, a specified value of incremental inductance is meaningless unless both of the concurrent dynamic (a-c) and polarizing (d-c) levels are stated. The dynamic voltage level can be measured as described above. The polarizing current can be measured as suggested in paragraph 3.13, or the polarizing voltage across the inductor can be measured with a high-resistance d-c voltmeter. Both dynamic and polarizing levels can vary while the bridge is being balanced.

*Method (a) is preferable for small polarizing currents, while method (b) is demanded for large polarizing currents.

The nonlinear core, especially when energized at higher levels, can introduce substantial harmonics into the system, and therefore a sharply tuned null detector is required for the measurement of iron-core inductors.

3.14.2 DISTRIBUTED CAPACITANCE. Because of the distributed capacitance of the inductor, series inductance and resistance are not constant with changing frequency. As the natural frequency of the inductor is approached, the effective inductance increases and then falls rapidly to zero at the natural frequency, where the basic or d-c inductance and the distributed capacitance are in parallel resonance. Beyond the natural frequency, the inductor has capacitive reactance, which the bridge cannot measure. The effective resistance of the inductor comes to a maximum at the natural frequency.

The natural frequency of an inductor with a large inductance can be quite low, and this is the reason for the correction specified in paragraph 2.3. If the natural frequency of the inductor is only slightly above the operating frequency, the effective inductance measured by the bridge will depart markedly from the basic low-frequency inductance. Moreover, although the bridge may be balanced for the fundamental frequency applied, it will not be balanced for harmonic frequencies. The harmonic voltages present in the detector output may be great enough to obscure the fundamental voltage and prevent the precise determination of a true balance unless a filter system (refer to paragraph 1.3.3) is inserted to suppress the harmonics.

To avoid errors caused by the nearness of the natural frequency and to reduce the danger of induced spurious voltages, the operating frequency should be as low as practicable. A frequency of 1000 cps is generally satisfactory for all but large values of inductance, say above 100 millihenrys.

3.14.3 STRAY PICKUP. When an external standard is used and the unknown inductance is large, care should be taken that there is no mutual inductance between these external inductors, and that stray voltages from the generator, input transformer, or other source are not induced in the windings. (On the other hand, the Type 1482 Standard Inductors are highly astatic.) Where large inductances, and therefore large impedances, are involved, it is always necessary to guard against this danger of pickup.

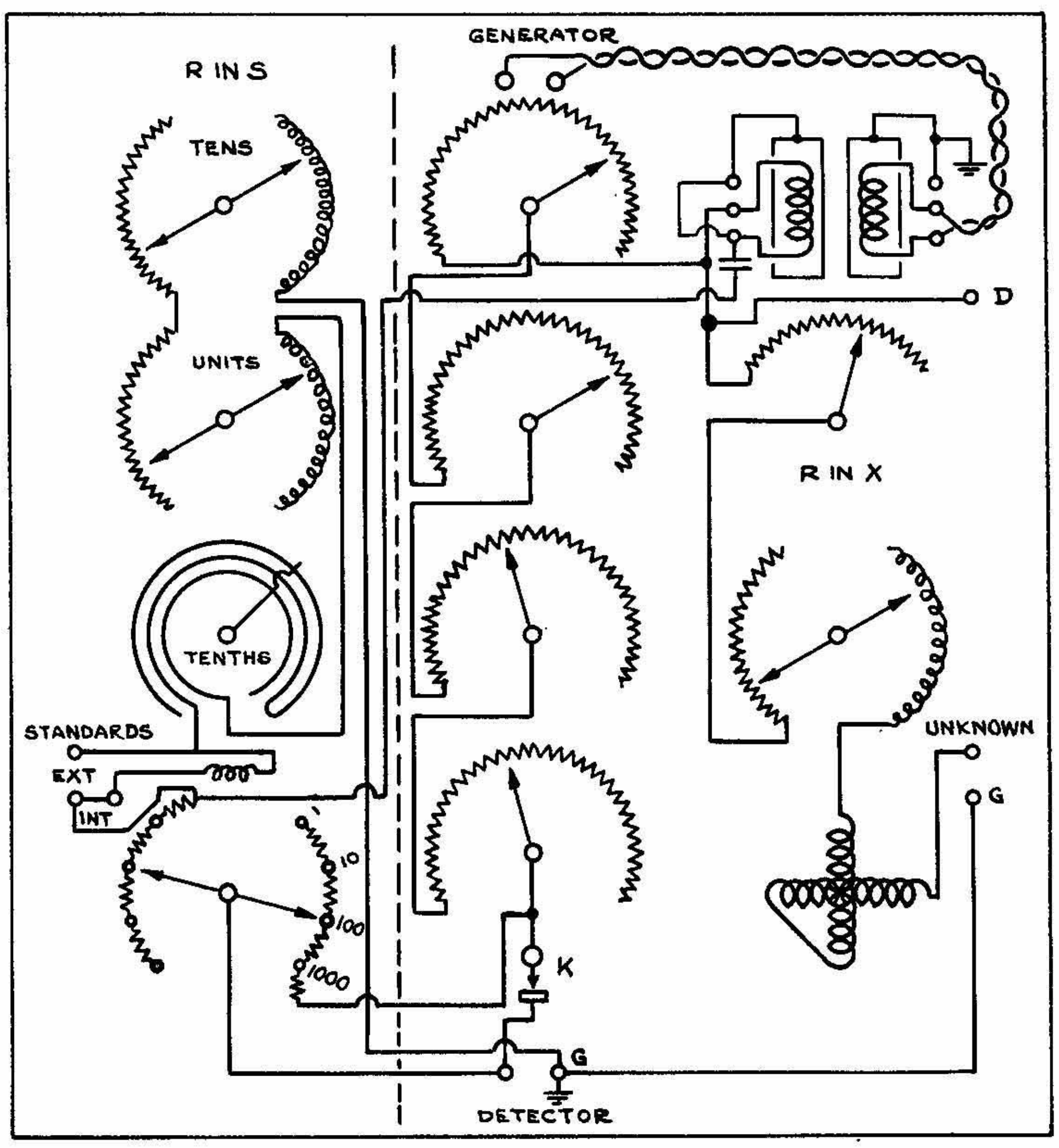

Figure 8. Schematic Wiring Diagram, Type 667-A Inductance Bridge.

Section 4
SERVICE AND MAINTENANCE

4.1 GENERAL. The following service information, together with that given in preceding sections, should enable the user to locate and correct ordinary difficulties resulting from normal use. Major problems should be referred to our Service Department, which will cooperate as much as possible by furnishing information and instructions as well as by supplying any replacement parts needed.

When notifying our Service Department of any difficulties in operation or service, specify the serial and type numbers of the instrument. Also give a complete report of trouble encountered, and steps taken to eliminate the trouble. Before returning an instrument or part for repair, please write to our Service Department, requesting a Returned Material Tag, which includes shipping instructions. Use of this tag will insure proper handling and identification. A purchase order covering repair of material returned should also be forwarded to avoid unnecessary delay.

4.2 ROUTINE MAINTENANCE.

4.2.1 DECADE SWITCH CONTACTS. Use very fine sandpaper on a block to smooth decade switch contacts, and remove dirt and filings with a fine brush. Remove old lubricant with a solution of half ether and half alcohol, wipe the residue with a clean cloth, and apply a thin coat of high-grade lubricant, such as Lubrico MD-T-419 (Master Lubricant Co., Philadelphia, Pa.).

4.2.2 SLIDE WIRE RESISTOR. The slide wire that makes up the TENTHS control on the R IN S decade must be serviced frequently if the bridge is in constant use. Clean the wires and contact blades with a solution of half ethyl alcohol and half ether, rubbing off with a clean, lint-free cloth. Never use water or saliva. Then apply a small amount of high-grade clock oil to the wires.

If the blades become grooved, dress them with very fine sandpaper to remove the grooves, and then buff them to remove any sharp edges or burrs which tend to wear the wires. (This will not be necessary with the newer type of enclosed slide wire.)

CAUTION

Do not use any form of grease on the slide wire. Grease collects dirt and abrasive material, which will accelerate the wear of the slide wire and blades.

4.3 RESISTANCE MEASUREMENTS. Before trying to check the internal resistances in the bridge, remove the STANDARDS shorting link and turn the K switch (under the snap button) fully counterclockwise (open). Check d-c resistances as described in steps a through g below, using a Wheatstone bridge.

a. The MICROHENRYS switches are merely resistance decades of 100, 10, 1, and 0.1 ohms, as marked on the panel. These are the values between each successive contact on each decade. Set the MULTIPLIER to 1000 and measure between D and the ungrounded DETECTOR terminals. This will give the value: B + 0.015 ohm.

b. To check the compensating resistors R_{BO} individually, set all four R IN X switches to zero, and measure from the D terminal to the ungrounded DETECTOR terminal. Adjust the MULTIPLIER control for different values of R_{BO} (refer to paragraph 2.4).

c. To check the MULTIPLIER resistors, measure from the ungrounded DETECTOR terminal to the lower EXT STANDARDS terminal. Adjust the MULTIPLIER control for different values of R_A (refer to paragraph 1.2.2b).

d. The R IN S switches are also resistance decades, of values corresponding to panel marking. These decades are composed of two sections, one of which is the resistance decade and the other the compensating winding of practically zero resistance. These decades are in series with the one-ohm slide wire. The composite R_S is measured from the DETECTOR ground terminal to the upper EXT STANDARDS terminal.

e. The R IN X switches follow the panel markings in resistance values, but accumulate in resistance from the zero end; i.e., 200 ohms is the total of 100 plus 100 ohms, etc. Measure the D terminal to the ungrounded UNKNOWN terminal. This checks the resistance of the variable inductor, plus the resistance introduced by the R IN X switches.

f. To measure the resistance of the variable inductor (MICROHENRYS dial), repeat step e with both R IN X controls set at zero. The value should be from 0.140 to 0.155 ohm.

g. To determine the resistance of the internal toroidal standard, measure between the upper EXT and the INT STANDARDS terminals. For this particular bridge, Serial No. 418 , this should be a value of about 3,423 ohms.

4.4 INDUCTANCE MEASUREMENTS. The over-all accuracy of the bridge may be checked in the various inductance ranges by direct measurements made upon a series of accurately known standard inductors with non-magnetic cores. Correction for C_T loading (paragraph 2.3) must be applied for the larger standards and lead inductance must be determined for the smaller standards (paragraph 3.5.2). If Type 1482 Standard Inductors are used, their certificate values are given more precisely than the bridge data can be read, so that any discrepancy exceeding the bridge specifications of $\pm(0.2\% + 1\mu h)$ can be attributed to:

a. calibration errors in the bridge components,
b. lack of skill in attaining a true bridge balance,
c. excessive R IN X, or
d. existence of stray pick-up.

APPENDIX

SUMMARY OF SYMBOLS AND EQUATIONS

A a numerical factor indicated by the MULTIPLIER switch setting.

A' value of A at final balance.

B composite setting of the MICROHENRYS switches.

$B_{partial}$ reading of the TENS and HUNDREDS MICROHENRYS switches.

B' value of B at final balance.

ΔB $B' - B$

B_X, B_S values of B in substitution measurements.

C capacitance of tuning capacitor (resonance bridge).

C_T internal residual capacitance across UNKNOWN terminals.

D dissipation factor of tuning capacitor.

K coefficient of coupling between primary and secondary windings.

L_T total inductance of primary and secondary windings in series.

L_1 self-inductance of primary winding of mutual inductor.

L_2 self-inductance of secondary winding of mutual inductor.

L_{aid} value of L_T with aiding M.

L_{opp} value of L_T with opposing M.

L_1' indicated inductance of L_1 (Campbell bridge measurement).

L_D setting of MICROHENRYS dial.

L_O inductance of leads to unknown inductor.

L_P inductance of variable inductor (Figure 3) controlled by MICROHENRYS dial (not the dial reading).

$L_{P\,max}$ maximum inductance of P arm exclusive of L_X.

L_S inductance of internal toroidal standard.

L_S' inductance of an external standard.

L_X series inductance of the unknown inductor.

ΔL_X incremental increase of L_X due to loading by C_T.

ρ fractional increase in L_X due to loading by C_T.

M mutual inductance between primary and secondary windings.

Q storage factor of unknown inductor.

R_A variable resistance (Figure 2) adjusted by MULTIPLIER control.

R_B variable resistance (Figure 2) controlled by MICROHENRYS switches.

R_B' value of R_B at final balance.

R_{BO} compensating resistance (Figure 3) adjusted by MULTIPLIER control.

R_C resistance of tuning capacitor (resonance bridge).

R_{LP} resistance of internal variable inductor.

R_{LP}' value of R_{LP} at final balance.

ΔR_{LP} $R_{LP}' - R_{LP}$.

R_{LS} resistance of the internal standard inductor.

R_P variable resistance (Figure 2) adjusted by R IN X controls.

R_P' value of R_P at final balance.

ΔR_P $R_P' - R_P$

R_S variable resistance (Figure 2) adjusted by R IN S controls.

r residual zero setting value of R_S.

R_S' value of R_S at final balance.

ΔR_S $R_S' - R_S$.

R_X series a-c resistance of the unknown inductor.

$(R_X)_{D\text{-}C}$ d-c resistance of unknown inductor or resistor.

ω $2\pi f$ (radians per second).

EQUATIONS

(Equations marked * are the working equations used in obtaining the desired unknown data from the parameters of the balanced bridge.)

(1) $L_X = L_S \frac{R_B}{R_A}$

(2) $R_X = (R_S + R_{LS})\frac{R_B}{R_A} - R_P$

(3) $L_X = L_S \frac{R_B}{R_A} - L_P$

(4) $R_X = (R_S + R_{LS})\frac{R_B}{R_A} - (R_P + R_{LP})$

(5)* $\rho = \frac{\Delta L_X}{L_X} \doteq \omega^2 L_X C_T$

(6)* True $L_X = (1 - \rho)(L_X$ as measured)

Loading correction for larger inductors at higher frequencies.

(7) $L_X = \frac{R_B}{R_A} L_S + \frac{R_{BO}}{R_A} L_S - L_{P\,max} + L_D$

(8)* $L_X = AB + L_D$ microhenrys

Direct measurement, internal standard, neglecting leads.

(9)* $L_X = AB + L_D - L_O$ microhenrys

Direct measurement, internal standard, allowing for leads.

(10)* $L_X = B_{partial} + L_D$ microhenrys

Direct measurement, internal standard, allowing for leads.

(11)* $L_X = \frac{AB}{1000} L'_S$ henrys

Direct measurement, external standard.

(12)* $L_X = \frac{B_X}{B_S} L'_S$

Substitution measurement.

(13)* R_S = Indicated (R IN S) + r ohms

(14) $R_{LP} + R_P = (R_{LS} + R_S)\frac{R_{BO} + R_B}{R_A}$

(15) $R'_{LP} + R'_P + R_X = (R_{LS} + R'_S)\frac{R_{BO} + R'_B}{R_A}$

(16) $$R_X = \frac{R_{LS}(R'_B - R_B) + (R'_S - R_S)R_{BO} + R'_S R'_B - R_S R_B}{R_A} - (R'_P - R_P) - (R'_{LP} - R_{LP})$$

(17)* $$R_X = \frac{A}{1000}\left[R'_S B' + R_{LS}\Delta B - R_S B\right] + 0.015\Delta R_S - \Delta R_P - \Delta R_{LP}$$

Direct measurement, internal standard, has indeterminate terms.

(18) $R_X + R_C = \frac{R_B}{R_A} R_S$

(19)* $R_X = \frac{ABR_S}{1000} - R_C$ ohms

Resonance bridge, preferable to Equation (17).

(20)* $R_C = \frac{D}{\omega C}$

For evaluating R_C, if significant.

(21) $R_X = \frac{\omega L_X}{Q}$

(22) $R_X + R_C = \frac{\omega L_X}{Q} + \frac{D}{\omega C} = \omega L_X\left(\frac{1}{Q} + D\right)$

(23)* $L_X \doteq \frac{1}{\omega^2 C}$ henrys

Resonance bridge, approximation only; direct measurement more accurate.

(24)* $(R_X)_{D\text{-}C} = \frac{R_B}{R_A} R_S = \frac{ABR_S}{1000}$ ohms

Wheatstone bridge measurement.

(25) $L_T = L_1 + L_2 \pm 2M$

(26) $K = \frac{M}{\sqrt{L_1 L_2}}$

(27)* $M = \frac{L_{aid} - L_{opp}}{4}$

Direct measurement.

(28)* $M = \frac{L_1 - L'_1}{1 + \frac{A'B'}{1000}}$

Campbell bridge measurement.

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