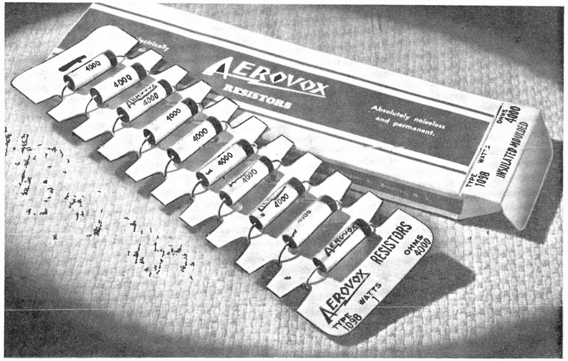

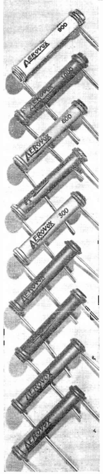

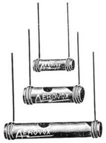

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Measurement of Inductance

PART 2

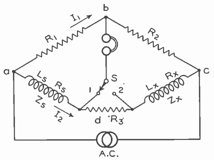
(Part 1 published July, 1938)

By the Engineering Department, Aerovox Corporation

INDUCTANCE BRIDGES

AS in the measurement of capacitance there are a large number of bridge circuits available for the measurement of self-inductance. All bridge measurements are comparisons in which the unknown is compared to some known quantity. This known quantity may be another inductance or a capacitance. In the discussion of the various circuits both types of standards will be treated with in detail. In general a capacitance standard is to be preferred to an inductance standard as capacitance standards are more easily constructed and maintained. The sensitivity and accuracy of inductance bridges depend on the same factors as the sensitivity and accuracy of capacity bridges as discussed in the April 1938 issue of the Aerovox Research Worker. No attempt will be made in this issue to duplicate this analysis as the principles involved with respect to capacitance bridges apply directly to inductance bridges.

The simplest inductance bridge is the straight comparison bridge. The bridge consists of ratio arms of resistances and a standard inductance. The standard inductance may be fixed or variable. If the standard inductance is fixed the ratio arms must be continuously variable. The circuit of such a bridge is given in Figure 1. The inductance bridge must have a provision for inserting a resistance, R_3, in series with either the standard inductance or the unknown inductance as the resistance of the unknown may be less than the standard. In capacitance measurements the equivalent series resistance of the unknown condenser is rarely less than the resistance of the standard condenser. This condition is not unusual in inductance measurements and provision must be made for inserting the power factor resistance in either arm.



$$L_X = \frac{R_2}{R_1} L_S$$

FOR S IN POSITION 1

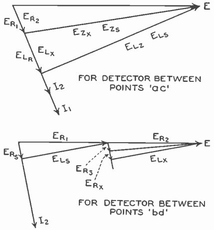
$$R_X = \frac{R_2}{R_1} R_S - R_3$$

FOR S IN POSITION 2

$$R_X = \frac{R_2}{R_1} (R_S + R_3)$$

Figure 1

The bridge is adjusted for minimum signal, care being taken to make sure an absolute minimum is reached. This is not difficult when a variable standard is used, but some difficulty may be had if the standard inductance is fixed and the ratio arms are varied. This is caused by the fact that the two balance conditions are not independent. To obtain a balance with a fixed standard inductance, the ratio arms are first adjusted for a minimum tone in the detector. Then the resistance R_3 is varied. If the signal decreases with an adjustment of R_3 the adjustment is continued until a minimum signal is reached after which the ratio arms are readjusted for a closer balance. This process is continued until a null point is reached. If the adjustment of R_3 causes the signal strength to increase rather than decrease, the ratio is not correct. The resistance R_3 is then set at some other value and the ratio is readjusted for a minimum. This is continued until a balance is reached. If the standard inductance is variable, the ratio arms are set to some value and the standard inductance is varied for minimum signal. The resistance R_3 is then adjusted for a balance. The vector diagrams for the bridge circuit of Figure 1 are given in Figures 2a and 2b.



Figures 2A and 2B

The power source and the detector used will depend on the inductance to be measured. Choke coils and iron-cored coils should be measured at 60 or 120 cycles, the frequency at which they are used. Air core coils can be measured at 1000 cycles. Radio frequency coils should be measured at their operating frequency. Power frequencies can be obtained directly from the line through transformers, and 120 cycles can be gotten from the ripple of a full wave rectifier. The circuit for such a power supply is given in Figure 3.

The transformer T_1 should be a 110 volt universal filament transformer having a secondary tapped from 1.5 to 35 volts. The capacity *C* should be adjusted for the best wave shape at the 120 cycle terminals. The best value will depend on the transformer and the d.c. load drawn from the power supply. For higher frequencies oscillators are desirable. Circuits of suitable oscillators and amplifiers are given in The Research Worker, May 1938.

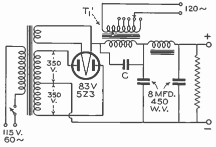


Figure 3

The detector used will depend on the frequency of the voltage applied to the bridge and the sensitivity desired. For 60 and 120 cycles some form of amplifier and a.c. voltmeter is necessary as the lack of aural sensitivity precludes the use of phones. At frequencies greater than 250 cycles phones are satisfactory and when preceded by an amplifier are entirely satisfactory. Amplifiers used in connection with bridges should be carefully constructed to eliminate hum which will tend to mask the signal as a balance is approached.

When iron core chokes are to be measured provision must be made to pass a polarizing current through the choke. This can be done by connecting the polarizing source as shown in Figure 4. The choke coil in series with the battery must be large compared with inductance of the coil being measured. The capacity of *C* must be large so that its reactance is small compared to the reactance of the coil. This circuit is not as satisfactory for the measurement of iron core coils as the Hay bridge.

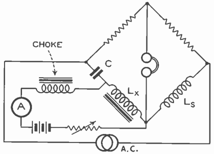


Figure 4

The Hay bridge for the measurement of incremental inductance is given in Figure 5. The equations of the bridge are not independent of frequency but if the Q or

$$\frac{\omega L}{R}$$

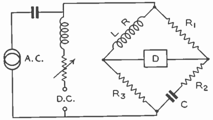
of the coil under test is greater than 10 the equations for inductance reduce to

$$L = R_1 R_3 C \text{ HENRIES}$$

$$R = \frac{R_1 R_3}{R_2}$$

with an error of 1%.

The power source for this bridge can be as that in Figure 3, with the 120 cycle sources connected in series with the d.c. polarizing circuit. A potentiometer should be used to control the d.c. current through the circuit. The resistance R_3 must be capable of carrying the polarizing current flowing through the choke coil. The resistance R_1 and R_2 must be continuously variable if *C* is fixed. Since this bridge is not independent of frequency a generator having a fairly pure sine wave output must be used or difficulty will be experienced in obtaining a sharp balance.



$$L = R_1 R_3 \frac{C}{(1+\omega^2 C^2 R_2^2)} \quad \text{or} \quad L = R_1 R_3 C$$

$$\text{when } \omega^2 C^2 R_2^2 < \frac{1}{100}$$

$$R = R_1 R_3 \frac{\omega^2 C^2 R_2}{(1+\omega^2 C^2 R_2^2)} \quad \text{or} \quad R = \frac{R_1 R_3}{R_2}$$

Figure 5A

This is not serious when phones are used because the ear will differentiate between the fundamental and the harmonics provided the harmonics are not too strong. With an indicating type of balance meter a generator having a high harmonic content will be unsatisfactory.

The following constants have been found satisfactory for the measurement of inductances from 1 to 100 henries:

$C = 1$ and 10 mfd.
$R_3 = 1000$ ohms
R_1 variable from 0 to 10,000 ohms
R_2 variable from 0 to 50,000 ohms

As noted above R_3 must be capable of carrying the polarizing current of the coil being measured without affecting the value of the resistance. For coils having a value of *Q* greater than 10 the resistance R_1 can be calibrated directly in henries. For coils having values of *Q* as high as 10, the readings can be taken from R_1 and multiplied by a correction factor or calculated directly from the general equation of the bridge. The following table gives multiplying factors for R_1R_3C to obtain the correct values of inductance.

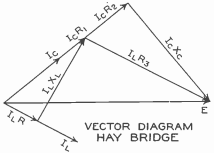


Figure 5B

When *Q* is 10 or less:

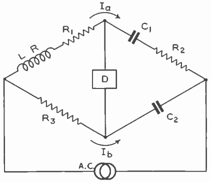
Q	F
1	0.500
2	0.750
3	0.900
4	0.942
5	0.962
6	0.972
7	0.980
8	0.985
9	0.988
10	0.990

$$Q = \frac{1}{\omega C R_2}$$

Another bridge which uses a condenser as a comparison standard is the Owens bridge. The bridge circuit is given in the diagram of Figure 6. The resistance R_1 can be made zero if C_1 is made continuously variable. R_3 is made adjustable in units of 10, and R_2 is continuously variable. The inductance is directly proportional to the product of $C_2R_2R_3$ and the equivalent series resistance of the coil is equal to

$$\frac{C_2}{C_1} R_3$$

If C_1 can not be made continuously variable R_1 and R_2 must be variable. R_3 is fixed and the balance is obtained by successive adjustments of R_1 and R_2. The balance is independent of frequency and wave form of the applied voltage provided the circuit elements are independent of current and voltage.



$$L = C_2 R_2 R_3 \text{ HENRIES} \qquad R = \frac{C_2}{C_1} R_3 - R_1 \text{ OHMS}$$

OWEN'S BRIDGE

Figure 6A

This bridge has the advantage of covering an extremely wide range of values with a relatively small variation in standards. A bridge having the following constants has a range from 0 to 11.111 henries and 0 to 111.11 henries. R_3, 1000 and 10,000 ohms; C_2, 1 mfd.; C_1, 0 to 3.999 mfd.; R_2, 0 to 11.111 ohms. With C_1 and C_2 fixed at 0.3 mfd. and R_3 adjustable over a range from 1 to 1000 ohms; R_1 and R_2 continuously variable from 0 to 111.11 ohms, the bridge has a range from 0.3 microhenries to 3 henries.

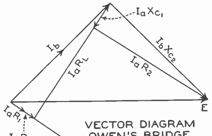


Figure 6B

For the measurement of iron core chokes which must be measured with a polarizing current, the power supply and detector terminals can be interchanged so that polarizing current can be supplied through the power terminals.

The Anderson bridge is another type of inductance bridge using a condenser as standard. This bridge has 6 arms or impedances instead of 4 arms as in the other bridge circuits discussed. Because of this feature the Anderson bridge has a wider range. The Anderson bridge is slightly more difficult to balance although it can be used for precision measurements. The circuit and vector diagram is given in Figure 7. In setting up the Anderson bridge R_2 and R_4 are equal ratio arms. R_1 is fixed and R_3 is variable. A non-inductive resistance *r* is added in series with *L* and the balance is obtained by adjusting R_3 and the resistance in series with the inductance.

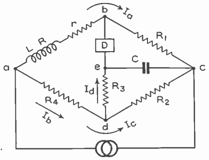
The capacity of *C* must be chosen of such value that *L/C* makes $R = R_1$ of reasonable value. R_2 and R_4 are made approximately equal to one-half of R or R_1. The balance is then obtained by varying R_3 and the resistance in series with *L*.

R_3 may have a fairly large value and as it is in series with the detector the sensitivity of the bridge will be decreased. To overcome this difficulty the power may be fed into the points *b-e* and the detector connected to the points *a-c*. The input voltage must be increased because of the resistance R_3 in series with the power supply.

The vector diagram of the Anderson bridge is shown in Figure 7. When the bridge is balanced the voltage drop between the points *b-e* is zero, which means that the drop across R_1 which is equal to I_aR_1 is equal to the drop across C which is

$$-jI_d X_c$$

This drop must be in phase with the current I_a so that the current I_d will lead the current I_a by 90°.



$$L = C\left[R_3\left(1+\frac{R_4}{R_2}\right)+R_4\right] \text{ HENRIES}$$

ANDERSON'S BRIDGE

$$R = \frac{R_1 R_4}{R_2} \text{ OHMS}$$

Figure 7A

The current I_a will lag the voltage *E* since the circuit contains resistance and inductance. Thus I_a and I_d are established. The drop through R_3 is in phase with the current I_d and therefore in phase with the drop I_aX_L.

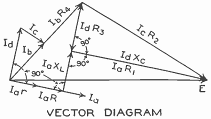


Figure 7B

Thus the vector sum of I_aX_L and I_dR_3 locates the end of the vector I_bR_4 and also the vector I_cR_2 as the sum of these last two vectors must equal the impressed voltage *E*.