Magnetic shielding test setup using the Helmholtz structure.

Test station for checking power chokes on inductance bridge.

Testing and Measuring INDUCTORS

Methods and equipment used to measure inductance, self resonance, distributed capacitance, and "Q" of air-core and iron-core coils. Bridges and "Q" meters are commonly employed. Tolerances allowed and MIL-Specs are covered.

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INDUCTORS are widely used in electronic and electrical equipment. Designers of such coils generally design them for a specific application whenever the end use is known. The performance of a coil, besides being affected by its shape, size, and core material, can be drastically influenced by the mode of operation. In order to establish the performance of an inductor under actual field conditions, measurements should simulate, as closely as possible, the operating conditions of that coil.

Every inductor has associated with it spurious resistance and capacitance. Losses due to these spurious elements must be taken into account when any measurements are made and the measuring method selected accordingly. In some cases the inductance of the coil will be of primary importance and will have to be measured accurately, whereas the effective series and shunt losses need only be estimated roughly.

For other cases, however, especially if measurements are required on high-"Q" powdered-iron cores whose losses are small and difficult to measure, the determination of such losses will require much greater accuracy. Most bridges used in making measurements compare impedances to standards built into the bridge. A choice of a bridge circuit for the measurement depends entirely on the frequency, the inductance range, and the "Q" value of the coil to be measured. The bridge must have the necessary sensitivity, and its standards must cover the impedance range of the coil. The null-detecting device must have sufficient sensitivity to give visible or audible indication of balance. It may also be necessary to provide some frequency discrimination between bridge and detector to reduce erroneous balances due to harmonic distortion.

The basic bridge circuit is shown in Fig. 1. In order to achieve balance, two conditions must be met: 1. the magnitude $Z_x \cdot Z1 = Z2 \cdot Z3$; and 2. the sum of the phase angles of opposite arms must be equal: $\theta_x + \theta 1 = \theta 2 + \theta 3$.

Several types of bridges are used in inductance measurements. The *Maxwell bridge* permits measurements of inductance in terms of capacitance. A capacitance has many advantages over an inductor as a standard: it is small in size, easy to shield, and has practically no external field.

The Maxwell bridge (Fig. 2) is a convenient way of determining coil inductance within certain ranges. Difficulty may arise when the coil "Q" is very high. For such a case $R1$ is of very large value and resistance balance becomes difficult to determine. For very low values of coil "Q's" (which fall within the range of inductive resistors rather than coils),

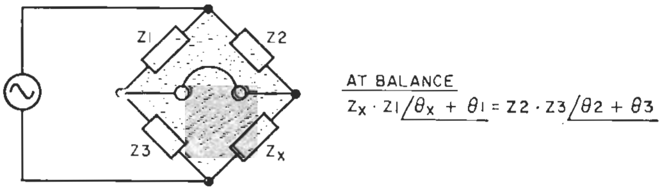
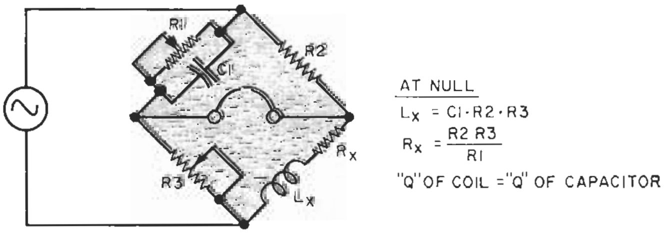


Fig. 1. Basic bridge circuit used to measure unknown impedance.

Fig. 2. The Maxwell bridge employs a capacitor as the standard.



the Maxwell bridge exhibits very poor convergence of balance, an effect known as "sliding balance." This is caused by interaction between the controls where a new apparent balance is achieved each time the resistors in the different arms of the bridge are changed. The balance point appears to slide and settles only gradually to its final point.

For inductance measurements on coils with high "Q" values, the *Hay bridge* is more convenient. The Hay bridge differs from the Maxwell bridge in having resistance $R1$ in series with the standard capacitor, $C1$, instead of in parallel with it. For large phase angles this requires a low value of the series resistance and gives better balance for high "Q" coils.

The two types of bridges have a definite area of overlap. As a rough "rule of thumb," the Hay bridge would be used if the coil "Q" is above 10.

Another bridge often used is the *Owen bridge* shown in Fig. 3. It has the advantage of having both adjustable elements, $R3$ and $C3$, in the same arm. This makes the reactive adjustment independent of the resistive adjustment, thus avoiding the interlocking effect or "sliding balance." Another advantage of the Owen circuit is that $R3$ which is used to determine L_X, is a high-accuracy decade resistance, thus giving accurate determination of the inductance value. Also, if one can arrange to prevent direct current from passing through the generator, then inductance measurements with superimposed d.c. in the coil are facilitated. The disadvantage of the Owen bridge is that a decade capacitor is required. This tends to become rather large if a high-"Q" coil is measured.

As an alternative, $C3$ can be changed to a small value in parallel with $R3$. These two forms of the Owen bridge are related in the same way as the Maxwell and Hay circuits. A modified Owen bridge, with a fixed capacitor replacing decade capacitor $C3$, is available for inductance measurements. An adjustable resistor, $R4$, is added in the arm in series with the unknown coil to be measured. The unknown R_X has to be found by a difference of two readings of $R4$. This may seriously affect accuracy if the value of $R4$ is large.

Another useful circuit for inductor measurements is the resonance bridge shown in Fig. 4A. Since three arms are resistances, balance can be obtained only if the fourth arm is also purely resistive in over-all effect. This condition is met if $|X_L|=|X_C|$. At balance: $R_X=R2R3/R1$; $L_X=1/(2\pi f)^2C$. This bridge can be used to determine L_X and R_X if C and the frequency are known. It can also be used to determine frequency if the values of L_X and C are known.

Self-resonant Frequency

When an inductor is placed in a circuit or across the terminals of a bridge, it represents a complex network which includes, in addition to its inductance, resistance and capacitance. If we neglect flux leakage between turns of the winding, which in most cases is insignificant, we can simplify the coil equivalent circuit to that shown in Fig. 4B.

$R1$ represents the copper winding resistance and is generally independent of frequency. Only at extremely high frequencies would $R1$ appear to rise in value due to "skin effect." $R2$, representing core losses, is a combination of three frequency-dependent losses: eddy current, hysteresis, and residual losses. These losses increase with frequency and flux level. Capacitor C represents the total shunt capacitance effect of the "between turns" capacitance and the capacitance from each turn to the core or ground. This capacitance forms a parallel circuit with inductance L which resonates at the self-resonant frequency of the coil.

Due to this self-resonant effect, only those inductance measurements made far below the self-resonance of the coil will give the true inductance value of the coil. As the bridge frequency approaches the self-resonant frequency, the apparent inductance measured differs (increases) from the true inductance according to the relationship: $L_{(apparent)} = L_{(true)}/(1-[f/f_o]^2)$ where f is the bridge frequency and f_o is the frequency of self-resonance.

The self-resonant frequency not only affects the apparent inductance of the coil but also adds dielectric losses to it. In addition, it limits the "useful" frequency range of the coil.

Of the several methods available for measuring self-resonant frequency of a coil, the simplest one utilizes a generator and voltmeter, as indicated in the circuit of Fig. 4C.

The generator voltage E_G is kept constant while the frequency dial is swept in search of the resonance point. Resonance occurs when the voltage across resistor R reaches a minimum (dip). The frequency at which this occurs is the self-resonant frequency of the coil. The resistor should be selected so that its value is small compared to the coil impedance at resonance. This impedance is equal to "Q" × $2\pi f_oL$.

For any coil with a core whose permeability changes considerably with voltage level variations, E_G should be of such magnitude as to impress the same voltage across the coil as the coil will be subjected to under actual operating conditions. This method gives an accurate indication of the self-resonant frequency, particularly if the coil "Q" is of moderate value. For coils with low "Q" values, the resonance point can be difficult to establish since the impedance peak of the inductor is fairly flat.

A further difficulty arises in measuring self-resonance in coils where the inductance varies with frequency. Quite elaborate setups with phase measurements are then required.

The net effective distributed capacitance (C_D) of the coil has a direct effect on the self-resonant frequency. This capacitance can be measured directly on some commercial bridges such as the *Boonton* "Q"-meter. In general, the measuring frequency should be selected far above the self-resonant frequency of the coil.

For coils whose true inductance is independent of frequency, one can calculate C_D by resonating the coil first with a capacitor, $C1$, to the frequency f_1 then with another capacitor value, $C2$, to the frequency f_2.

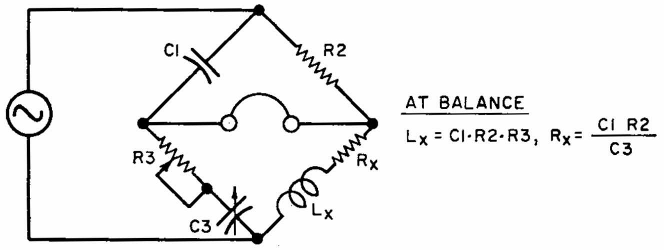
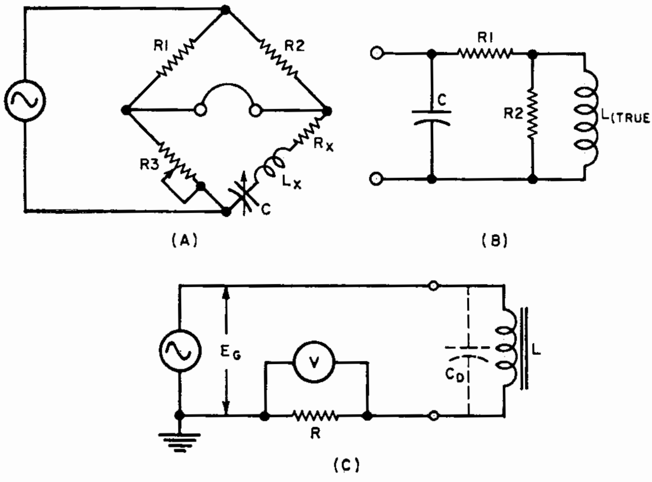


Fig. 3. Owen bridge has both adjustable elements in same arm.

Fig. 4. (A) Resonance bridge. (B) The equivalent circuit of a coil. (C) Measuring self-resonant frequency of an inductor.



TESTS PERFORMED & TOLERANCES

Most inductors used as smoothing chokes for d.c. power supplies are required to carry a relatively large direct current in their windings. Their a.c. flux swing is generally small, consequently the LI^2 determines the size of the unit. These chokes are generally designed on laminated core structures with gaps in their magnetic paths. The inductance requirement for this type of coil is usually a specified minimum value, while the d.c. resistance of the winding has a maximum specified limit (mostly restricted by the power dissipation in the winding and efficiency of the circuit). Core losses for this type of coil are seldom of interest. Frequently these coils will have tolerance requirements for their inductance values but, for the most part they are typically −20% to +50%.

Much tighter tolerances are required on inductors used as filter elements in electric-wave filters, tuning coils, transmission circuits, and in measuring apparatus. Here inductance tolerances are quite severe: from 2% or 3% to less than ¼% are not uncommon.

Also, the "Q" requirements of the coils are limited: mostly as a minimum "Q" value but not infrequently one finds a "Q" tolerance of ±5% or ±10%. These types of coils, generally precision audio coils with wide frequency ranges of operation, will (and should) also have minimum self-resonant frequencies specified. Power inductors are usually tested for inductance and d.c. resistance on a 100% basis, the inductance tolerance being −20%, +50%, with the d.c. resistance tolerance ranging from 5% to 20%, depending on wire size used.

Besides inductance and d.c. resistance, inductors are tested for dielectric strength (typically 1500 V r.m.s.), and insulation resistance (typically 10^{10} ohms at 500 V d.c.). Many inductors are constructed to meet MIL-T-27B specifications: they are either metal encased per Grade 1 or 4 of MIL-T-27B specification, or are encapsulated per Grade 2 or 5, or open units impregnated to meet requirements of Grade 3 or 6 of MIL-T-27B. Units generally cover a maximum operating temperature range of from class R (105°C) to class T (170°C) and U (over 170°C) operation.

In order to maintain close tolerances on precision toroidal coils, they are usually checked against a "standard" coil during the winding process. For that purpose toroidal winding machines may be interconnected to their own deviation bridges. This enables the operator to wind the coil to a point where the deviation bridge indicates a match. To further assure a minimum inductance shift, coils may be strain-relieved and inductance-trimmed to the required value. After processing, the coils at their final stage are again checked for compliance with their electrical and mechanical parameters.

Samples of each lot of coils are selected on a specified AQL level for additional tests consisting of: 1. Self-resonance test, 2. Electromagnetic and electrostatic coupling between units (where applicable), 3. Electrostatic and magnetic shielding (when specified), and 4. "Q" factor.

On military items and high-reliability coils, additional tests are performed on samples selected from those units which have successfully passed the above tests. These additional tests are outlined in detail in the MIL-T-27B Spec under Group C tests. These include a series of mechanical shock and vibration tests, temperature cycling and thermal shock, temperature rise, terminal strength, immersion and moisture resistance.

Currently available are inductors which have successfully passed mechanical shocks of 800 g's and vibrations of 4000 Hz in three mutually perpendicular axes.

Inductors built for high reliability or military use are generally required to pass stringent qualification tests before qualification approval is granted. These tests are listed in Table VII of MIL-T-27B and cover complete electrical, mechanical, and environmental test requirements. Included in qualification tests, if specified, is a corona-discharge test. This test is generally performed only during qualification inspection and only if specifically called for, will it be performed as an acceptance test.

Coils which are magnetically shielded are placed in the center of an energized Helmholtz structure and a voltmeter is connected across the inductor. The inductor is then oriented until maximum voltage appears across the inductor. This voltage must generally be very low, on the order of from 1 or 2 μV to less than 100 μV.

Another test for the effectiveness of the magnetic shielding of inductors is to measure the strength of the magnetic field in the immediate vicinity of the inductor—a field caused by the flux leaving the core. For this test, the inductor is energized and a search coil is moved around the outside of the inductor. The highest voltage the search coil may register on the v.t.v.m. is specified for individual inductors ranging from several millivolts to 0.1 volt.

One of the most time-consuming tests performed on inductors is the moisture-resistance test. After an initial conditioning of 24 hours, the unit is placed in a humidity chamber maintained at 90 to 98% relative humidity. In the chamber the unit is subjected to 10 continuous cycles of 24 hours each, with alternate periods of temperature exposure, varying from +65°C to +25°C and from +25°C to −10°C. Included in five of the cycles is a period of mechanical vibration. ▲

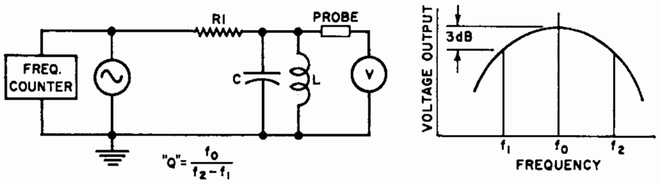


Fig. 5. The 3-dB bandwidth method of measuring coil "Q."

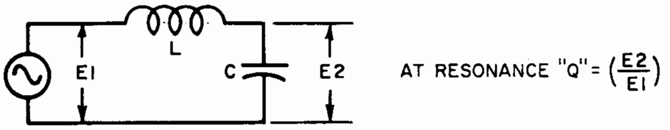


Fig. 6. The voltage-rise method of measuring coil "Q."

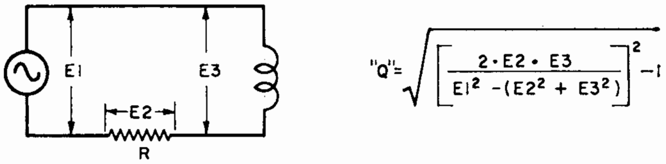
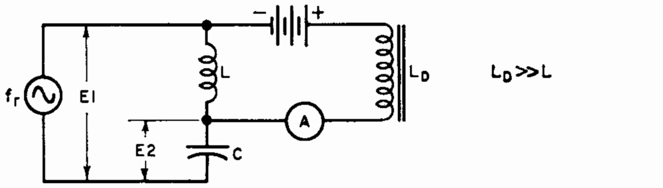


Fig. 7. Three voltage readings are required for this method.



L IS THE COIL UNDER TEST
C IS THE CAPACITOR REQUIRED TO TUNE L TO THE DESIRED FREQ. f_r
C SHOULD BE A HIGH "Q" CAPACITOR (SILVERED MICA OR POLYSTYRENE)

Fig. 8. Measuring inductor with a metered amount of d.c.

The distributed capacitance of the coil is then computed:

$$C_D = \frac{\left(\frac{f_1}{f_2}\right)^2 \times C1 - C2}{1 - \left(\frac{f_1}{f_2}\right)^2}$$

Next to the inductance of a coil, the most important parameter describing the efficiency or quality of the inductor is quality-factor or "Q." When an alternating current is flowing through a coil, energy is stored in the coil during a portion of the cycle. Most of the stored energy is fed back into the circuit later in the cycle. The difference between the stored energy and the returned energy is the energy dissipated in the coil. A perfect coil with no losses would return *all* the energy stored. The "Q" or figure of merit is the ratio of stored to dissipated energy per cycle. "Q" is also the quotient of the inductive reactance of the coil and the resistive losses. For a series representation, "Q" $= 2\pi fL/R_{(series)}$; for a parallel representation, "Q" $= R_{(parallel)}/2\pi fL$.

There are several methods of measuring "Q": the most common are the damping-factor method (energy dissipation), the 3-dB bandwidth method, and the voltage-rise method. The 3-dB bandwidth method is illustrated in Fig. 5.

In all "Q" measurements, the "Q" of the entire circuit is measured. Therefore, in order to determine the coil "Q," choose capacitors of very high "Q" values (*e.g.*, silvered mica or polystyrene) so that the "Q" of the circuit will virtually equal the coil "Q."

In the circuit of Fig. 5, $R1$ should be selected so it will not load the circuit. It should be at least 100 times the QX_L impedance. Also, the voltmeter must have high input impedance or, alternatively, a high-impedance probe should be used.

Most commercial "Q" bridges utilize the voltage-rise method for "Q" measurements (Fig. 6). Capacitor C should have a very high "Q" value and a capacitance sufficient to resonate the coil

(*Continued on page* 71)

Testing Inductors

(*Continued from page 32*)

at the desired frequency. The voltmeter used for measuring $E2$ should have high input impedance and an input capacitance which is negligible with respect to C. At resonance, voltage $E1$ reaches a minimum (dip) and voltage $E2$ peaks.

Another method of measuring "Q," Fig. 7, is indicated in an arrangement in which three voltage readings are made. R should be a non-inductive resistor and all voltage readings must be true r.m.s.

Coils Carrying D.C. and R.F.

When measuring coils carrying direct current in their windings, special care has to be taken: 1. to avoid providing a path which will enable d.c. to bypass the coil; 2. to keep the d.c. from passing through the generator; and 3. in some methods, the d.c. circuit impedance must be made high with respect to the coil impedance so as not to "load" the coil.

One way of meeting all three requirements is shown in Fig. 8. L_D is an inductor used to isolate the d.c. source and keep it from loading the a.c. impedance of the coil. L_D should be of such a value that its a.c. impedance under the test condition is over 50 times the coil impedance.

Basically, the circuit test procedure is the same as for the voltage-rise method of "Q" measurement. At resonance the "Q" $= E2/E1$ and $L = 1/(2\pi f_r)^2C$.

The advantages of this method are its simplicity, accuracy, and yield of two parameters (inductance and "Q") with one set of measurements. Its limitation is the availability of an inductor for L_D which, while carrying the required d.c., maintains a sufficiently high impedance.

Radio-frequency coil measurements do not differ, in principle, from measurements made on coils at any other frequency. However, some special precautions are required for the r.f. tests.

It is especially important to use short leads when measuring coils with low inductance and low resistance. It may be necessary to subtract from the readings the bridge terminals and lead inductances.

If the inductance is of relatively large value for the frequency of measurement, the inductor may have to be shielded to prevent coupling to outside spurious fields.

If an unshielded coil is to be measured, the coil must be kept close to the terminal posts of the bridge, but kept as far away as practical from the bridge chassis and any other conductive surface. Such surfaces adjacent to the coil —even an operator's hand too close to the coil—may cause erroneous "Q" and inductance readings. ▲