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HIGH-Q COILS AT AUDIO FREQUENCIES

By J. B. Schaefer*

Much attention has been given to the Q of coils for use at radio frequencies. The advantages of high-Q coils, the design and structural considerations necessary for obtaining a high Q, and the methods of measuring Q, at these frequencies have been treated quite thoroughly. A similar fund of information about coils for audio frequencies is not available. This discussion will, therefore, be confined to coils for frequencies below approximately 20,000 cycles. Attention will be given to (a) types of coil construction, (b) the important characteristics of coils, (c) features of coils having laminated steel cores, (d) methods of measurement of Q, and (e) uses of coils and the effect of Q in circuit operation.

Types of Coil Construction

The four most common classes of coil construction for audio frequencies are: (1) air-core coils, (2) toroid coils with a permalloy-dust core, (3) coils with an iron-dust core, and (4) coils with a laminated steel core.

One type of air-core coil is formed by winding the turns on a spool. Flexible leads are then attached, the coil is impregnated, and is then ready for use. Another type is simply a paper-supported layer-wound coil. For a given weight of wire, certain proportions of the coil dimensions will give a maximum Q for an air-core coil, and this fact is usually considered in the design of a coil.

The toroid coil with a permalloy core provides the highest values of Q now attainable. The core is made up of fine particles of nickel-iron alloy of high permeability and low loss, molded with a binder under pressure into the shape of a washer. The wire is wound from a shuttle so that it completely surrounds the core, leaving a hole in the center.

The iron-dust coil employs a core of iron-dust particles molded into such shapes as are determined by the allowable size of the coil and the frequency at which maximum Q is desired. The winding is similar to that in the ordinary air-core coil.

Of the four types, the laminated steel core is most commonly used. The laminations are usually shaped like the letter "F", and are so stacked that the only gap in the magnetic path occurs at the center of the coil. This gap may be of any length from almost zero up to about one inch.

Important Characteristics of Coils

The ideal coil would have (1) an unvarying inductance, (2) no distributed capacitance, (3) no resistance, and (4) no external magnetic field. No such coil can be made. In fact the most important characteristics of a coil are those which measure its departure from the ideal.

The inductance of a coil depends directly on (the number of turns)^2 and inversely on the reluctance of the core as determined by the effective length, the cross-sectional area, and the permeability of the magnetic flux path. Increased inductance may be obtained by increasing the number of turns, or decreasing the reluctance of the core, as is done by decreasing the length, increasing the area, or improving the permeability of the flux path.

No matter what winding structure is used, each turn has capacitance relative to other turns, as well as to the core and case. The net effect can usually be represented by a single capacitance across the coil terminals (called the "distributed capacitance") plus a capacitance to ground. By proper design, both of these capacitances can usually be made negligible for audio frequencies.

The losses in a coil comprise chiefly those in the core and in the wire. The latter loss is usually subdivided into (1) losses due to the d-c resistance of the winding, and (2) eddy-current losses in the wire, but in a properly designed coil the eddy losses in the wire are small. Figure 1(a) shows the d-c resistance R_c and, the core-loss resistance, R_{sh}. The latter can be transformed to the equivalent series resistance R_1, as shown in Fig. 1(b), and it can then be added to R_c to give R, the effective

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coil resistance. It is important to note that, because the core loss depends on the frequency, R_i varies with frequency and thus any value of the effective resistance of a coil is of significance only at a particular frequency. This fact cannot be stressed too strongly.

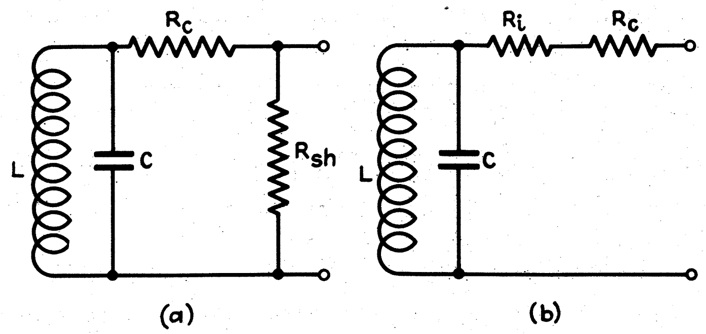

Fig. 1 - Coil losses as Equivalent series resistances.
R_c = d-c resistance of coil.
R_{sh} = lumped core losses = E^2/W_i where W_i = core loss in watts.
R_i = series equivalent of R_{sh} = W_i/I^2.
R = effective or a-c resistance = $R_c + R_i$.
C = effective distributed capacity.

The Q of a coil is defined as the ratio of its reactance to its effective resistance, X/R. The meaning of this term may be better understood by comparing it to the power factor of the coil, $R/\sqrt{X^2 + R^2}$. If X is at least seven times R, the power factor $R/\sqrt{X^2 + R^2}$ differs from R/X by not more than one percent. That is, if the value of Q exceeds 7, the power factor is the reciprocal of Q. For lower values of Q, the power factor can be computed from the exact formula, $p = 1/\sqrt{Q^2 + 1}$.

Maximum Q is obtained in a coil when R_i equals R_c, just as maximum efficiency is obtained in an electrical machine when the copper loss equals the iron loss. Both the core and the copper loss of a coil can be reduced by increasing the size. Thus, if the design is correct, the Q will increase with size. To simplify the discussion here, a weight of approximately two pounds will be assumed for all coils. The Q of a given coil structure is practically constant over a considerable range of inductance values.

Often it is important that the inductance remain constant over a range of operating conditions. The following factors may affect the inductance: (1) frequency of operation, (2) magnitude of the a.c. or d.c. in the coil, (3) temperature of the coil, and (4) adjacent magnetic materials. The first three of these operate because they affect the permeability of the iron core. The temperature effect is more prominent in coils having small air gaps, since the expansion or contraction of the structure causes the air-gap length to vary by a greater relative amount. The effect of adjacent magnetic material on the inductance of a coil depends on the amount of stray flux which exists about the coil. Whether these various effects are large or negligibly small depends mainly on the length of the air gap. If in a coil having no air gap the permeability of the core is doubled, the inductance will be similarly doubled; if, however, there is an air gap of only 0.002 inch in length, the inductance will increase only 15 percent; while if the gap is one-half inch long, the inductance will increase only 2 percent.

Often it is desirable or essential that the coil carry some d.c. Under this condition the inclusion in the core of an air gap may serve not only to prevent saturation but to avoid distortion of the a-c waveform.

High-Q coils, like other inductive devices, generate a stray magnetic field in the surrounding medium. This field may or may not be troublesome, depending on the application. Air-core coils are the worst type in this respect, even when special winding shapes are used to reduce the stray field. The flux lines spread out from the coil in all directions and set up eddy currents in adjacent metal objects. This results in increased losses and an unstable inductance value.

The effect of even a small magnetic core is to localize most of the flux to a much smaller region, hence coils of this type almost invariably have a weaker stray field than the air-core type. Where an air gap in the core is used, its location is important. It should be so located that the fringing effect of the flux lines around the gap is a minimum.

The weaker the stray field around a coil, the greater is its so-called "self-shielding" factor. This is important particularly in filter work where two or more coils are often used in physical proximity to each other. In many cases not enough consideration is given to the place-

Table I

Characteristics of Various Types of Coils

Type of Coil	Frequency in Cycles	Q	Stability	Self-Shielding Effect	Relative Cost
Air Core	100 1,000 10,000	5 20 50	Excellent Excellent Excellent	Poor Poor Poor	Low Low Medium
Permalloy-Dust Core (Toroidal)	100 1,000 10,000	50 150 200	Excellent Excellent Excellent	Excellent Excellent Excellent	High High High
Iron-Dust Core	100 1,000 10,000	8 25 100	Good Good Good	Good Good Good	Medium Medium Medium
Laminated Steel Core (14-mil Laminations)	100 1,000 10,000	25 35 30	Fair Excellent Excellent	Good Good Good	Medium Low Low
Laminated Steel Core (3-mil Laminations)	100 1,000 10,000	20 60 50	Fair Excellent Excellent	Good Good Good	High Medium Medium

ment of such coils. It is generally appreciated in amplifier design that the input and output transformers must be separated even where the input transformer is well shielded. Yet in filters having two or more sections, where the desired difference in level between the input and output circuits may reach 40 db or more, coils are often placed quite without thought as to the possible coupling difficulties which may result from the stray fields.

With respect to the Q values, the superiority of the permalloy toroid coil is evident from Table I; it is the best of the coils available at this time. The high Q obtained is due to the combination of very high permeability and extremely low losses in the core material.

The air-core coil has a low Q at 100 cycles due to the low value of reactance. At 1000 cycles the reactance is ten times as great, but now the eddy-current losses in the wire are appreciable. At 10 kc., even when stranded wire is used, the losses increase and the Q is only 50 although the reactance is 100 times the 100-cycle value. The iron-dust coil has Q values which are consistantly higher than those of the air-core coil. This is due to the increased permeability, the losses being increased by only a small amount even at 10 kc.

When laminated steel cores are used, the values of Q are moderately good over the whole frequency range. When three-mil or five-mil laminations are used to reduce the eddy-current losses in the core, the Q values are quite high.

The stability of inductance of the air-core coil is due to the fact that the permeability of the air is constant with flux density, temperature, and other conditions. Because of the small air gap which is used in 100-cycle coils of the laminated-core type, such coils are somewhat less stable than those designed for higher frequencies.

The poor self-shielding of the air-core coil is usually offset by having a metal case, but unless this is large the Q is reduced considerably. Toroid coils are excellent in their self-shielding; such coils may be mounted close together without additional shielding. A coil having an iron-dust core rates fairly well as to self-shielding, although in use each one should be individually shielded. Coils using the laminated-core type of construction are not entirely self-shielding, but can usually be mounted quite close together in filters without serious ill effects on the filter characteristics. They have the distinct advantage that a metal shield will not affect the Q if the air gap is properly located.

The cost ratings (Table I) represent average values applicable to the small quantities which are commonly purchased for filter and equalizer construction. The air-core coil increases in cost at the higher frequencies due to the stranded wire with which it is wound. The toroid coils are high in cost due to winding difficulties when an automatic machine is not set up. When a laminated core is used, costs are higher for the low-frequency coils because a high-permeability, heat-treated metal must be used for the core if a good Q is to be obtained.

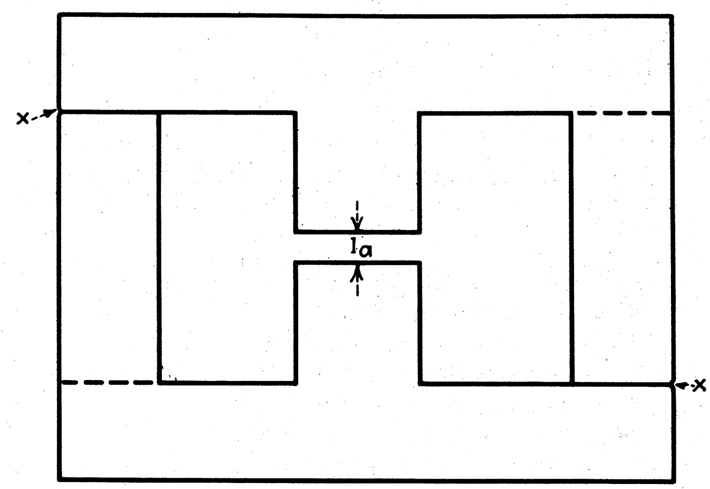

Fig. 2 - Core structure for laminated-core coil.

Figure 2 (a) illustrates a core structure widely used in the laminated-core type of coil. The joints at the points marked "X" are interleaved by reversing adjacent pairs of laminations. The only air gap in the completed stack is that which is shown as "l_a". The length of this gap determines the frequency at which a coil has its optimum Q, this is shown in Fig. 3. With a gap of 0.010 inch Q reaches a maximum value of 24 at 160 cycles. When the gap is 0.060 inch the maximum Q occurs at 540 cycles. Q in this instance is 45. Further increases in the air gap will continue to raise the frequency of maximum Q, as is shown. It is worthy of note that with a silicon-steel core the Q which can be obtained at the lower frequencies is definitely lower than at frequencies above approximately 1000 cycles. This may be explained as follows: At the higher frequencies for which the air gap is 0.250 inch or more, the permeability of the steel is not important insofar as its effect on the inductance and Q is concerned. The core loss is the principal factor which determines Q and if it is kept low Q will be high. On the other hand, at the low frequencies the air gap is much smaller and the inductance is determined not so much by the air gap as by the permeability of the core. The relatively low permeability of silicon steel thus reduces both the inductance and Q. When higher values of Q are desired at the low frequencies, the core is made of a high-permeability nickel-iron alloy instead of silicon steel.

These laminated-core coils have a wide range of usefulness. Reasonably good Q values can be obtained at any frequency up to 10 kc by designing the coil with the proper value of air gap. The range of inductances which may be obtained is broad enough to include all the values which are required in practice, and the physical size may be anything from small four-ounce coils with a Q of about 12 to large coils weighing thirty pounds or more.

Methods of Measurement of Q

Any of the familiar bridge circuits may be used to determine the Q of a coil within about 10 percent, if proper precautions are taken. The resistance units must remain constant over the frequency range of the measurements, and their reactive components must be negligible. The capacitances between various bridge arms must be made low, preferably by shielding. It is important that the power source and the null indicator be isolated from the bridge proper by balanced transformers with electrostatic shields.

The requirements for the power source are severe. Its frequency must be stable and accurately known; this is particularly important when the bridge balance and the measured inductance are functions of frequency. The harmonic content of the source may have to be held to a very low value. A 1-percent second harmonic may assume considerable importance of the fundamental is entirely balanced out in a bridge in which a balance does not exist for harmonics.

The most desirable null indicator is a high-gain selective amplifier with a rectifier output meter. The degree of selectivity necessary depends on the required accuracy and on the purity of the source signal. A simpler method of locating the null is to use a pair of headphones. Although this scheme is limited in practice by the characteristics of the ear and of the usual phones to frequencies between approximately 250 and 3000 cycles, it has the advantage that the ear can distinguish between the fundamental and its harmonics. This means that filters, although desirable, are not essential.

One very convenient means of measuring Q at frequencies up to several thousand cycles requires only a Wheatstone bridge, a variable standard condenser, an a-c source, and a null indicator. The coil to be measured is connecte in series with the condenser and the combination is connected in the bridge circuit as the "Unknown". The variable bridge resistance arm and the condenser are adjusted for balance; the Q can then be computed. The inductance is found from the series-resonant relation, $L/(6.28f)^2C$, and the resistance is given by the bridge setting. It is necessary that the frequency at which measurement is made and the voltage across the coil in the balanced bridge be approximately the same as in the normal use of the coil.

Effect of Q in Circuit Operation

Figure 3 shows the effect of Q in a shunt equalizer for providing a very gradual attenuation of the low frequencies. When Q is infinite, which means zero resistance in the coil, the attenuation increases continuously at lower frequencies as the coil reactance decreases. When the coil has enough resistance to give it a Q of only 30 at 1000 cycles the attenuation slopes off and reaches a value of 21 db at 50 cycles. From that point down the attenuation is determined only by the resistance of the coil, which remains substantially constant. The attenuation in this and the remaining drawings is $20 \log_{10}$

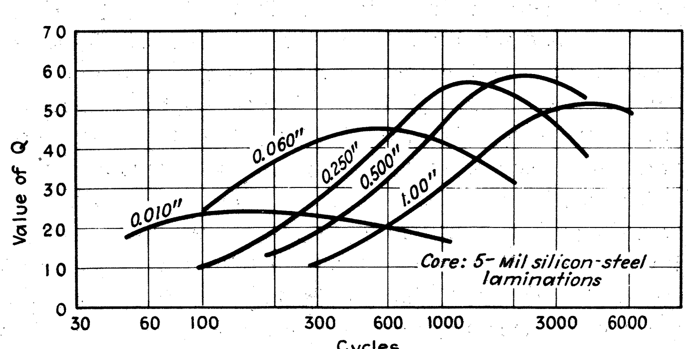

Fig. 3 - Variation of Q with frequency for different air-gaps.

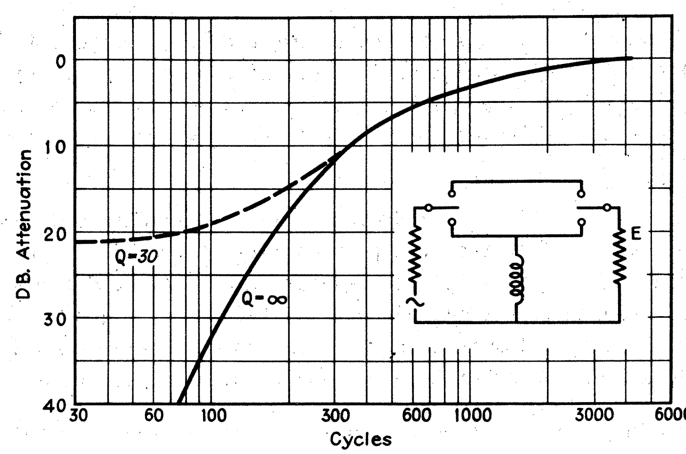

Fig. 4 - Attenuation of simple shunt equalizer.

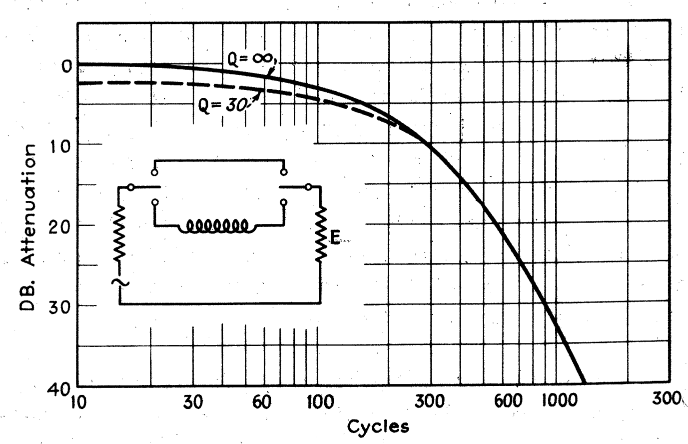

Fig. 5 - Attenuation of simple series equalizer.

(E_D/E_N), where E_D is the output voltage with the load connected directly to the source and E_N is the output voltage when the network (the equalizer or filter) is in circuit.

When a coil is used in the circuit shown in Fig. 4, the effect of Q is quite different. The attenuation above 10 db, (above about 300 cycles,) is not reduced by the finite Q of the coil. In fact if the resistance of the coil increases fast enough at frequencies above 250 cycles, the attenuation may be greater than that of a perfect coil.

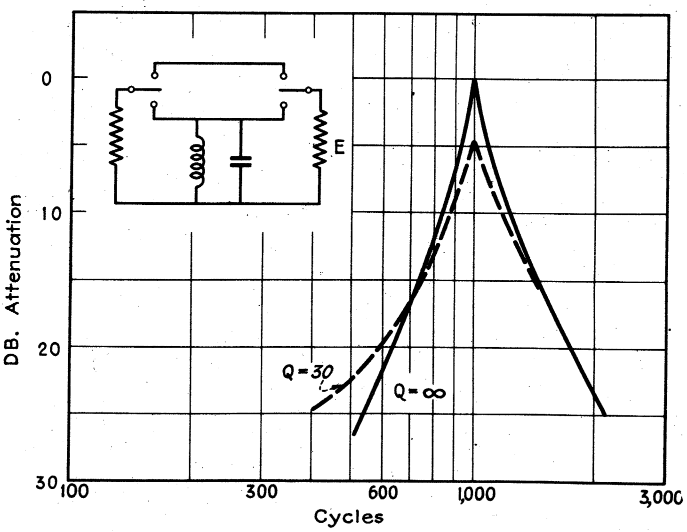

Fig. 6 - Attenuation of parallel resonant shunt equalizer.

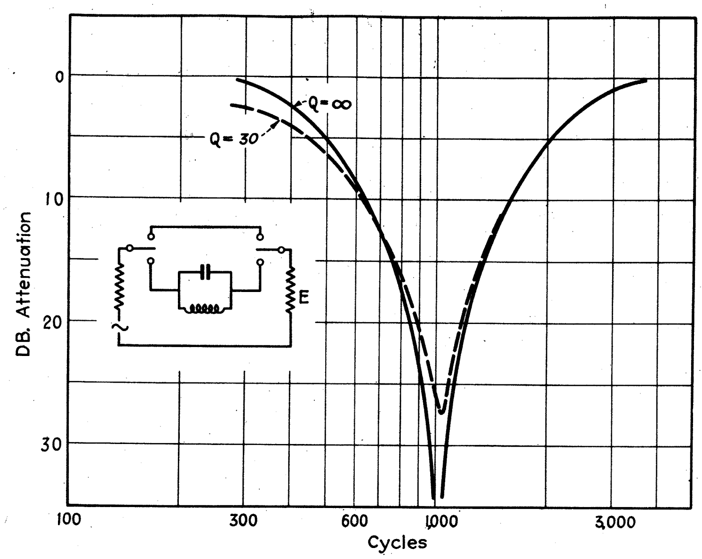

Fig. 7 - Attenuation of parallel resonant series equalizer.

At the low frequencies, however, a coil with a Q of 30 at 100 cycles will introduce an "insertion loss". This is due to the existence of the coil resistance in the series circuit even when the reactance is negligible.

In Fig. 5 is a typical resonance curve giving the attenuation of the parallel-resonant shunt equalizer. For the condition of infinite Q the impedance of the tuned circuit at resonance is infinite, and the attenuation is zero. When the coil has a Q of 30, the resonant impedance is a value such that an "insertion loss" of 5 db occurs. On the high-frequency side of resonance the attenuation increases as the condenser reactance decreases, and above 1500 cycles the Q of the coil does not affect the operation. On the low-frequency side, the circuit behavior is similar to that of Fig. 3, with the attenuation for a finite Q approaching a fixed value at the low frequencies.

The parallel-resonant circuit when used in the series connection has a characteristic as shown in Fig. 6. The attenuation with the coil of infinite Q is infinite at the resonant frequency, and approaches zero at frequencies several octaves away. When the coil has a Q of 30 at 1000 cycles, the resonant impedance is finite and limits the attenuation to 27.5 db. Above the resonance point the capacitive reactance predominates, and the Q of the coil is unimportant above 1500 cycles. At the low frequencies the resistance of the coil causes an insertion loss of several decibels.

The curve for coils of infinite Q in Fig. 8, has the typical flat top. When the coils have Q values of 20 at 1000 cycles, the resistance introduces an 8-db loss at the center of the pass band. The rounded shape of the curve in that vicinity is sometimes undesirable, and in such cases the coils should have the highest possible Q. Attenuation above 1500 cycles is substantially independent of coil Q, and at low frequencies the attenuation levels off toward a constant amount depending on the value of Q.

The attenuation characteristics as shown are based in each case upon a particular proportion of reactance and resistance elements. Any circuit, whether simple or complex, can be examined and the effect of Q predicted as in the examples, simply by giving consideration to the variation of Q and R with frequency. After deciding upon the necessary Q the comparisons given in Table I should enable the user to determine the type of coil which is required.

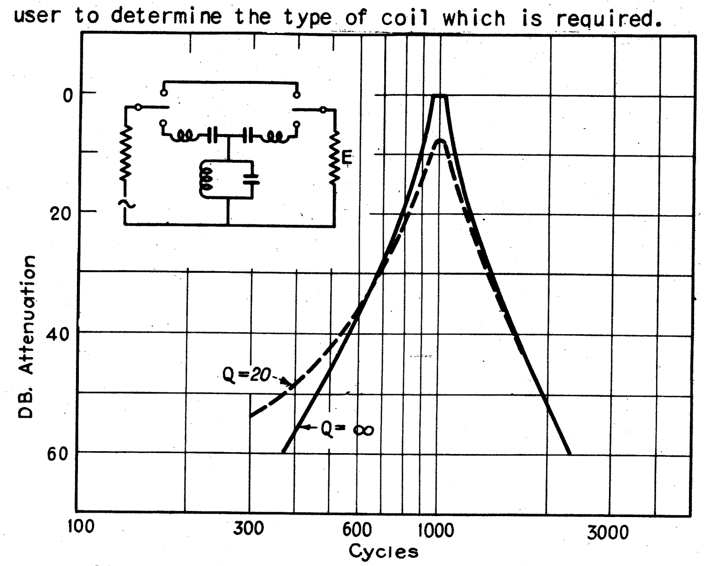

Fig. 8 - Attenuation of band-pass filter.