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INDUCTIVE AND REACTIVE EFFECTS OF LEADS AT ULTRA-HIGH FREQUENCIES

It is common for technicians working at radio frequencies up to several tens of megacycles to consider short, straight lengths of heavy wire unequivocally as efficient conductors. The d.c. resistance of such leads is so small as to be inconsequential. As an added refinement, conductors have been silver plated. The fact that even a straight, round wire has inductance has not attracted attention because the reactance resulting from that inductance has been too low at the common frequencies to be of consequence.

With television, FM, and various new electronic applications now introducing the technician to higher-frequency circuits, the behavior of leads and conductors assumes importance. At ultra high frequencies, leads which are excellent conductors at d.c. and low frequencies become impedances which must be reckoned with in all circuit work. Consider the case of a 2-inch length of No. 10 round copper wire. This lead has an approximate d.c. resistance of 0.00017 ohm, and unquestionably is a good conductor at common plate and screen voltages. Its inductance of 0.037 microhenry gives this short length of heavy wire a reactance of 0.000014 ohm at 60 cycles, which means that it still is a good conductor at power line frequencies and can become a dangerous short circuit. At 500 Mc., however, the reactance is 116.7 ohms, a respectable value. This figure does not take into effect skin effect at the high frequencies, which will increase the impedance of the wire still more.

Another interesting example is the inductance and reactance of the pigtail leads of a conventional mica capacitor. In the postage-stamp-size molded capacitor, these leads are made of No. 20 round wire. Even when the capacitor is mounted into a circuit with ½ inch of each pigtail, the total lead inductance is significant. Two straight ½-inch leads of No. 20 wire gives a total inductance of approximately 0.021 microhenry. This pigtail inductance (excluding the smaller natural inductance of the capacitor stack itself) is sufficient to resonate an 0.01-ufd. capacitor to 11 megacycles. At this frequency we have, instead of a simple capacitor, a tuned circuit. At lower frequencies, we have a capacitor, and at higher frequencies an inductor.

The inductance of a straight, round wire of a given length increases as the diameter of the wire decreases. This means simply that the inductance and reactance are greater for a fine-wire lead than for a heavier wire of the same length. These effects are pronounced at the ultra-high frequencies. When the diameter of the wire is halved, the inductance and reactance increase is approximately 1.17 times. When the length of the wire is increased, while holding the diameter constant, the increase in L and X_L is approximately 2.34 times.

Heavy metal bars are employed in some higher-frequency apparatus for the dual purpose of supporting components, such as capacitors and coils, and of conducting high-frequency currents. This is common in transmitters and in some test instruments. In some instances, the bars are used as conductors only. Often, such bars are a part of a tuning capacitor assembly.

As in the case of round wires, the inductance and reactance of a straight, rectangular bar also must be dealt with in higher-frequency circuit performance. The inductance and reactance of such a bar lead are of similar magnitude, although they are calculated in a slightly different manner. For illustration; the inductance of a 2-inch length of bar having a cross section 1/16 inch square is 0.04 microhenry. Its reactance at 200 Mc. is 50.24 ohms. A heavier 2-inch-long straight bar with a cross section ¼ inch square has an inductance of 0.027 microhenry and a 200-Mc. reactance of 33.9 ohms. As in the case of round wires, the inductance of a straight bar increases as the length is increased (cross section dimensions remaining the same) and increases also as the cross-sectional area is decreased (length remaining the same). The rate of increase, however, is somewhat different from that of round wires. For example, a 2-to-1 increase in the length only of a straight bar produces a 2½-to-1 change in inductance and reactance. Halving each side of the cross section of a square bar, while keeping the length constant, results in an inductance and reactance increase of 1.18 times.

Special Inductance Calculation

By now, the reader who has had some experience with the formulas for computing the inductance of coils must wonder how we came by the foregoing figures — how the inductance of straight conductors is calculated.

The formulas for this purpose are logarithmic. But they are not difficult to handle. The inductance formulas given in this article have been derived from those appearing in the

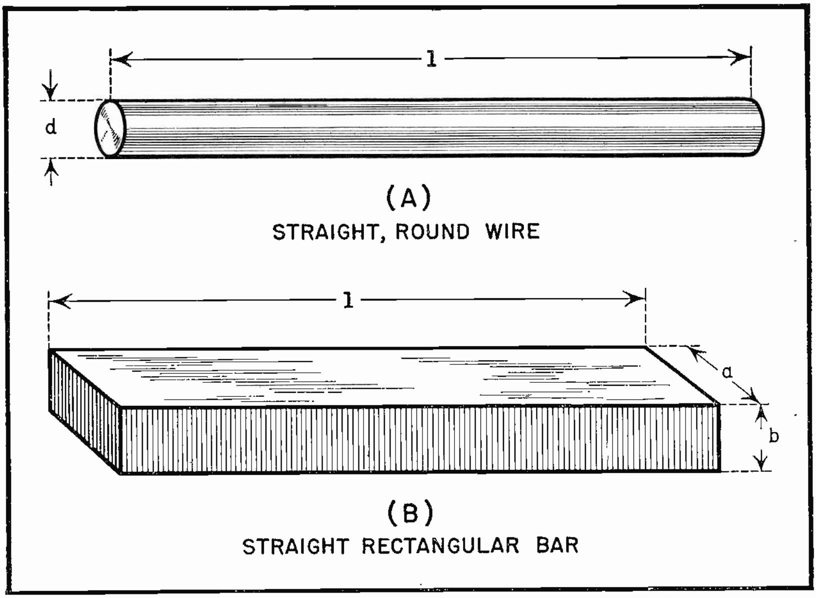


Fig. 1. Dimensions of common lead conductors.

National Bureau of Standards Circular C74, Radio Instruments and Measurements. Our derivations permit use of inches instead of centimeters.

For a straight, round wire (See Figure 1-A) of non-ferrous metal such as copper, the inductance formula is:

$$(1) \quad L = 0.00508\, l \,(2.303 \log_{10} 4\, l/d - 0.75) \text{ microhenries}$$

Where l = length of the wire in inches

d = diameter of the wire in inches

Since the inductance, as calculated by means of Equation (1), will decrease as the operating frequency is increased, the resulting error will become appreciable at very high radio frequencies. For better accuracy, it is necessary to take into consideration the permeability (μ) and resistivity (p) of the metal, and the operating frequency (f). Thus:

$$(2) \text{—} L = 0.00508\, l \,(2.303 \log_{10} 4\, l/d - 1 + \mu\delta) \text{ microhenries}$$

Where μ is the permeability of the wire metal (μ for copper is 1.0)

δ is obtained from the chart in Figure 2 in terms of "x". (x for copper at 20°C. — $0.272\, d\sqrt{f}$, where d is the diameter of the wire in inches, and f is the operating frequency in cycles per second).

The formula for reactance of a straight round wire is based upon the relationship $X_L = 6.28\ f\ L$ and is:

$$(3) \quad X_L = 0.0319(10^{-6}) f\, l \,(2.303 \log_{10} 4\, l/d - 1 + \mu\delta) \text{ ohms}$$

Where f is in cycles per second, and all other quantities are in the same units as in Equations (1) and (2).

The inductance formula for a metal bar of rectangular cross section is somewhat different from Equations

x	δ
0	0.250
0.5	0.250
1.0	0.249
1.5	0.247
2.0	0.240
2.5	0.228
3.0	0.211
3.5	0.191
4.0	0.1715
4.5	0.154
5.0	0.139
6.0	0.116
7.0	0.100
8.0	0.088
9.0	0.078
10.0	0.070
12.0	0.059
14.0	0.050
16.0	0.044
18.0	0.039
20.0	0.035
25.0	0.028
30.0	0.024
40.0	0.0175
50.0	0.014
60.0	0.012
70.0	0.010
80.0	0.009
90.0	0.008
100.0	0.007
∞	0.000

—From National Bureau of Standards Circular C74.

Fig. 2.

(1) and (2) for the inductance of a round wire:

$$(4)\quad L = 0.00508\, l\, (2.303 \log_{10} \frac{2\, l}{a + b} + 0.5 + 0.2235 \frac{a + b}{l})\ \text{microhenries}$$

the dimensions b, c, and l (See Figure 1-B) are in inches

The reactance of the straight bar is:

$$(5)\quad X_L = 0.0319(10^{-6}) f\, l\, (2.303 \log_{10} \frac{2\, l}{a + b} + 0.5 + 0.2235 \frac{a + b}{l})\ \text{ohms}$$

Importance of Skin Effect

Aside from d.c. ("ohmic") resistance, inductive reactance, and some inter-lead capacitance, skin effect tends to increase the total opposition offered to current flow in high-frequency leads and to produce higher attendant losses. It is skin effect which gives rise to the "high-frequency resistance" encountered in u.h.f. circuits. This peculiar resistance often is many times the d.c. resistance. The higher the operating frequency, the greater will be skin effects. Another interesting fact is that the best conductors (that is, metals with lowest resistivity) show the largest skin effect. The ratio of high-frequency resistance to d.c. resistance (R_{rf}/R_{dc}) is an important expression of conductor performance.

The question naturally arises as to the distinction between reactance (which might be construed as a sort of a.c. resistance) and high-frequency resistance. The latter actually is an in-phase component following the common characteristics manifested by resistance at d.c. and very low frequencies. High-frequency resistance is dependent upon several factors, one of them being the concentration of high-frequency currents on or near the outside, or skin, of the conductor. A large conductor, because of its increased surface area, shows lower high-frequency resistance than a smaller-sized one.

Low values of high-frequency resistance are exhibited by tubular conductors in which the wall is thin as compared to the diameter of the tubing. The same is true of strip conductor and of completely-braided wire and strip.

Complex Lead Impedance

From the foregoing discussions of lead reactance and of high-frequency lead resistance due to skin effect and ohmic resistance, it may be seen that a straight lead may at the very high frequencies become a respectable impedance. In the relationship $Z = R + jX_L$, R is the combined in-phase high-frequency resistance component including the ohmic resistance, skin effect, dielectric effects, effect of near-by conductors, and operating frequency effect. And X_L is the reactance due to the small inductance of the lead.

Precautions

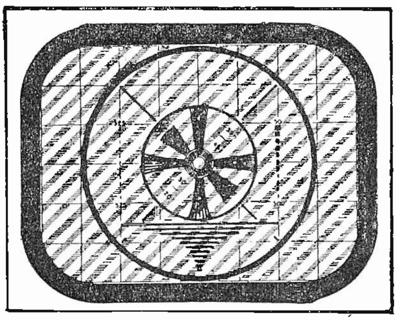
In higher-frequency circuits more than elsewhere, the old admonition to keep all leads not only short but straight is an important one. A careful study of the foregoing discussions reveals strikingly how failure to observe this rule in ultra-high-frequency apparatus will introduce not only surprising detuning effects, but unsuspected impedances which, through introduced losses, will absorb power at strategic points within the circuit.

In some higher-frequency circuits, the mere bending or kinking of a lead can so raise the inductance as to make its tuning effect felt.

TV INTERFERENCE . . . CAUSES AND REMEDIES

Television's present interference problems are growing pains and will probably be under industry control within the next few years. In the interim developmental period, during which the tv receivers are being redesigned, i-f frequencies shifted, etc., the Service Man has the field responsibility of solving tv interference problems on those tv receivers being manufactured in accordance with current standards. The following analysis of sources of tv interference is from "Service" magazine and a book to be published entitled, "TV - FM Antenna Installation" by Ira Kamen and Lewis Winner.

Television interference is transmitted from: (1) f-m stations; (2) f-m receivers; (3) tv receiver local oscillators; (4) tv receiver video circuits; (5) tv receiver sweep circuits; (6) prewar diathermy equipment; (7) electromedical and industrial apparatus; (8) radio amateurs, and (9) man-made devices.



(Courtesy Belmont Radio.)

Fig. 1. Typical r-f interference pattern on picture-tube screen.

Television interference is also a result of tv receivers having such design defects as poor image rejection, high level local oscillator radiation, insufficient shielding, and poor selectivity.

Analysis of Causes of Interference

To solve any interference problem, the nature of the interference must be thoroughly understood.

(1) F-M Stations: The second harmonic of the f-m band, 88 to 108 mc, lies in the upper tv band, 174 to 216 mc. Some of the present f-m transmitters do not have sufficient f-m second harmonic suppression and are a serious source of trouble which cannot be eliminated as the interference is on the same frequency as the tv station. F-m transmitter engineers are working on this problem feverishly, but until this problem is solved at the source, the tv set user will have to bear with the situation.

The only action the Service Man can take to discriminate against this on station f-m interference, is to install a directional antenna which can be adjusted so that the f-m station is not in the receiving pickup angle of the antennas.

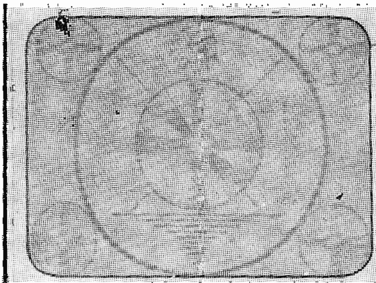
(2) F-M Receivers: The f-m receivers manufactured to date have their local oscillators set below the incoming 88- to 108-mc frequencies. This means that the local oscillators of the f-m receivers tune through channels 5 and 6. The local oscillators of the f-m receivers have been known to radiate interference into tv receivers located 1,000′ away from the f-m antenna. This on station f-m interference is a serious problem which will be with us for a number of years, until f-m manufacturers exercise better control over their designs.

An expensive method of preventing the f-m local oscillator signal from climbing the transmission line and radiating from the f-m antenna, is to install an r-f amplifier (f-m booster) between the f-m receiver and the transmission line. This amplifier will prevent the local oscillator signal from going into the transmission line and boost the f-m signal input to the f-m receiver.

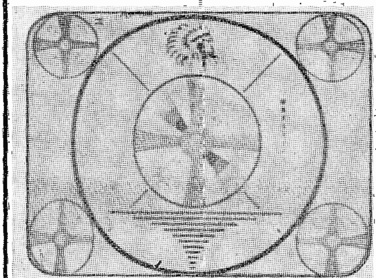
(3) TV Receiver Local Oscillators: Whenever tv receivers are tuned to channels 2, 3, 7, 8, and 9, their local oscillators are operating on channels 5, 6, 11, 12, and 13, respectively. This condition exists because the local oscillator frequency is on the high side and is equal to the incoming frequency, plus the i-f frequency; e. g., channel 2 (54-60 mc) plus 27 to 21 mc (i-f frequency) leaves the local oscillator at approximately 81 mc which is on the channel 5 band (76-82 mc). Similar examples can be set up to show how the local oscillator of a tv receiver tuned to channels 3, 7, 8, 9 transmits a signal on channels 6, 11, 12, and 13, respectively.

The tv industry is considering new i-f frequencies in their 1949 production to preclude this interference problem. An r-f preselector will also prevent the tv local oscillator signal from entering the antenna circuit. If the tv receivers are located adjacent to each other in a dealer's establishment the local oscillator interference problem can only be kept under control by judicious tuning of the tv receivers. When the tv receivers are close to each other, they couple directly through chassis radiation from their local oscillators. Therefore tv receivers being demonstrated must not be tuned to any combinations of channels where the interfering signals are developed.

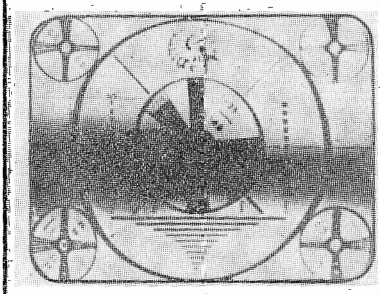
(4) TV Receiver Video Circuits: The tv receiver video circuits must reproduce currents varying from 60 cps to



(a)



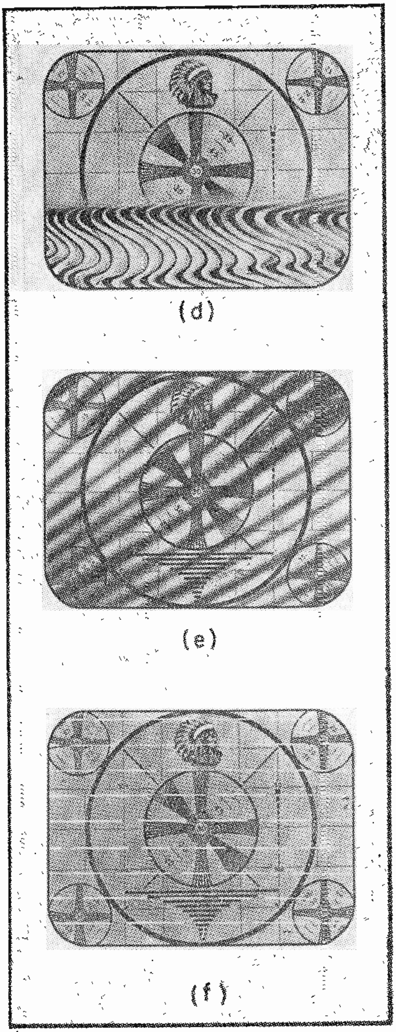
(b)



(c)

(Courtesy G.E.)

Fig. 2. Three types of interference are shown here. In (a) appears a weak picture affected by r-f pickup on the antenna. Weak diathermy interference is shown in (b), and in (c) we see the results of strong diathermy or hum in the video i-f, detector, or video output.



(Courtesy Admiral.)

Fig. 3. Three other types of interference which may disturb a tv picture. In (d) appears the results of interference from electromedical equipment. The view in (e) shows s-w transmitter interference and in (f) we have automobile ignition interference.

4.5 mc. In the frequency range of 60 cycles to 4.5 mc, we have the broadcast band which is .54 to 1.5 mc. It is therefore obvious that if the tv receiver video circuits or components were to radiate, they would induce interference signals into broadcast receivers in the neighboring area.

This video interference manifests itself in two ways:

(A) Background noise of variable signal strength which rides along behind broadcast stations. When the broadcast signals are weak, this background interference may be severe enough to mask the station program.

(B) Beeps of variable intensity which ride all over the broadcast band. These beeps are a result of the video signals beating with the steady broadcast station frequencies.

Most of the tv manufacturers are aware of this problem and are taking many wiring and shielding precautions to preclude radiation of interfering video signals. The Service Man can make an inexpensive shield from window screen material and completely shield the radiating tv receiver by pushing the screening between the chassis and the cabinet, so that the chassis is completely enclosed in the screen material. The screen material must be grounded to the chassis.

When making custom installations, care should be taken in shielding the video cable which connects the video amplifier output to the picture tube. Failure to shield this cable can result in high level induction fields which can radiate interference in a mile radius.

(5) TV Receiver Sweep Circuits: The tv receiver sweep circuits have saw-tooth wave forms which are rich

in harmonics. The horizontal sweep frequency of 15,750 cps harmonics produce beeps in the broadcast band when they beat with the broadcast station carriers.

Big picture tubes with their large sweep yokes are the worst offenders. In some dealer establishments where the a-m broadcast signals are weak, the beeps from the tv receivers makes a-m reception impossible on loop-operated receivers.

In addition to shielding, serious consideration should be given to locating the tv receiver, as far as possible from the a-m receiver picking up the interference. A shielded external a-m antenna will raise the a-m signal to beep ratio, so that the beeps will be lost in the background.

(6) Prewar Diathermy Equipment: The prewar diathermy equipment which is leased by many companies who sell diathermy treatments, is a constant source of interference. These diathermy equipments vary in frequency, have raw a-c on their plates and in general act as low-powered transmitters whose fundamental or harmonic frequencies are liable to operate on the tv, i-f, or r-f band.

The FCC is considering action to limit the use of these illegal equipments.

(7) **Electromedical and Industrial Apparatus:** The electromedical and industrial equipment manufacturers have been assigned and are using 26.96 to 27.28 mc for the fundamental frequency of their apparatus. This band lies directly in the tv i-f band. Whenever any of these equipments operate in the area of tv receivers using the current i-f frequencies, r-f or diathermy type interference are noted on the tv pictures.

The Service Man can minimize or eliminate this interference by installing a simple i-f trap in the antenna circuit. These traps are now commercially available and are simple capacitor-coil type series-resonant circuits which are in a shielded container and installed directly across the antenna terminals.

(8) Radio Amateurs: Much of the interference credited to hams is caused by items 1-7, although interference is possible from two ham bands: 21-21.5 mc (i-f interference) and 50-54 mc (spills over into channel 2).

The 21-21.5 mc problem can be minimized by filtering in the manner described under 7, while the 50-54 mc interference should be referred to the local office of the FCC for appropriate action.

(9) Man-Made Devices: The worst interference from man-made devices is from the little transmitter in the automobile ignition system, the spark plug. The bright spot in solving this problem is the development of a resistor spark plug.* This resistor spark plug reduces the radiated interference signals so that it is under 35 microvolts from .54 to 150 mc at 50′ from the spark plug. When all automobiles utilize this type of spark plug, the floating-specks will be washed from the tv screens.

Other devices as neon signs, ultraviolet lamps, motor sparking, etc., can all be suppressed at the source in the same manner as radio interference.

The final success of the tv industry in realizing full consumer acceptance will be dependent upon the satisfactory solution of the tv interference problem.

* Auto-Lite.