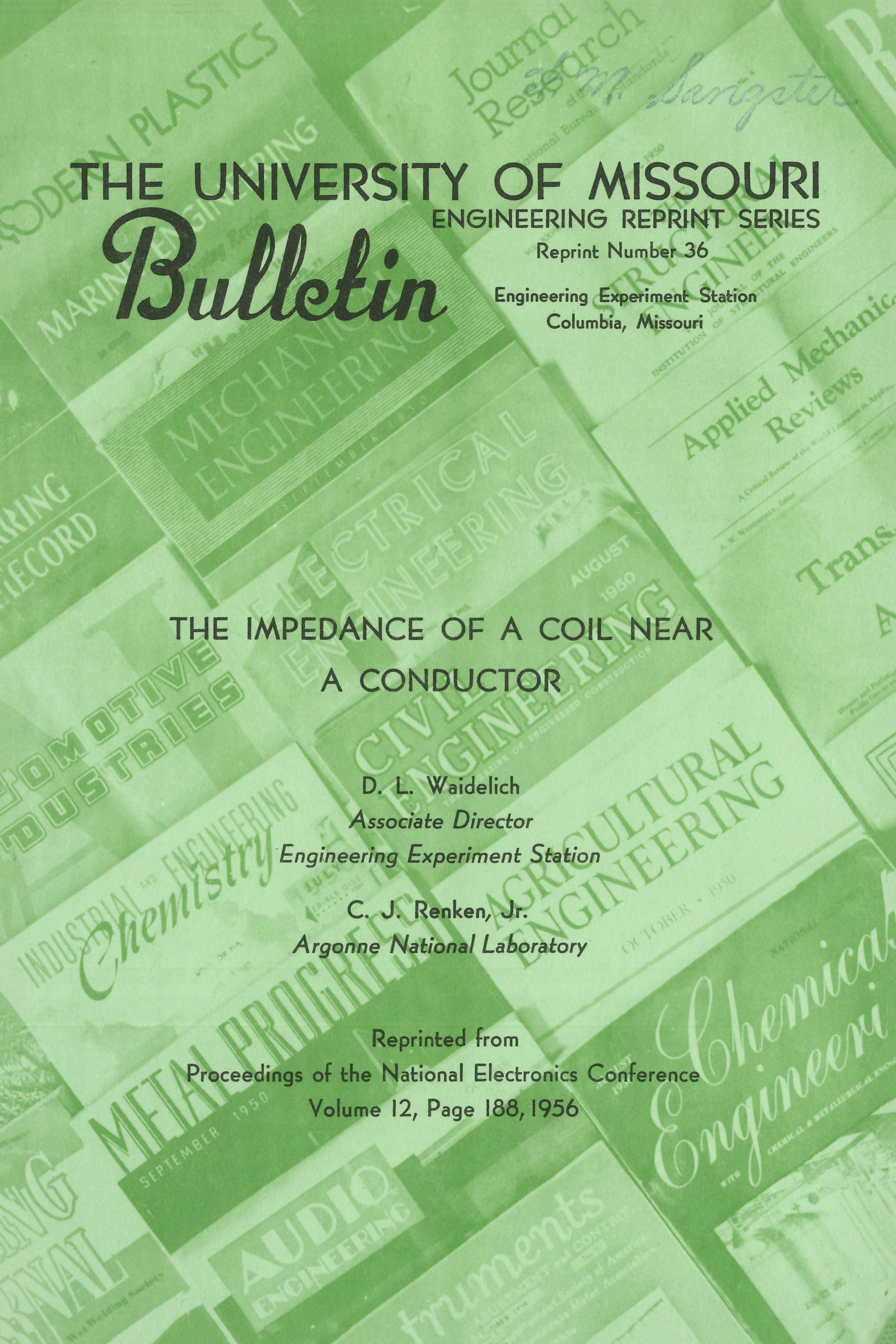

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THE IMPEDANCE OF A COIL NEAR A CONDUCTOR

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THE IMPEDANCE OF A COIL NEAR A CONDUCTOR

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Abstract.—The results are given of experiments undertaken to determine the manner in which the apparent inductance and resistance of an alternating current carrying coil changes when it is brought near a plate of non-ferrous metal. The experiments were undertaken with a view toward applying the results to uses in the instrumentation field. A theoretical analysis of the situation is included which gives good results when the assumptions upon which it is based are fulfilled. This analysis is based upon a modification of the image coil method. The limitations of the analysis are indicated. Most of the results are given graphically and show the change of coil inductance and resistance as functions of distance from coil to metal, frequency, metal conductivity and a combination of two dissimilar metals, one upon the other.

I. INTRODUCTION

In the nondestructive testing of metals by eddy current methods[1,4] a small probe coil is brought close to the surface of the metal, and the apparent change in impedance of the coil is determined by various methods. Certain items of information may be extracted from this change in impedance: among them are the thickness of a plated metal layer on the base metal, the presence of occlusions or voids in the metal, and the composition of an alloyed metal. The probe coil itself may have an air core, or it may have a magnetic core made of some ferrite. Apparently very little information has been published on the changes in impedance of such a coil near a metal, and this paper is an effort to supply some of this information. This study is concerned entirely with non-ferrous metals.

"Forster"[5] has made a theoretical analysis and experimental tests of the effect of a metal rod or tube as the core of a circular coil. An analysis and some experimental results will be presented here for the case of a coil with its axis perpendicular to the surface of a plane piece of metal. When the coil is energized, the resulting eddy currents flowing in the metal produce an apparent change in impedance or reflected impedance in the coil. This reflected impedance is a function of a number of variables, including the thickness of the metal, its conductivity and composition, the distance between the coil and the metal and the shape, size, number of turns and core material of the coil. The impedance will also depend upon the frequency if sinusoidal electrical currents are used, and upon the pulse shape and length if pulsed currents are employed.

II. ANALYSIS

The principle parts of the analysis are given here, while the details are available in the Appendix. This analysis of a coil near a conducting surface assumes

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[a] This work was completed under contract No. ANL-31-109-38-575 with Argonne National Laboratory, under the auspices of the U.S. Atomic Energy Commission.

a coil of negligible width and thickness compared to its diameter. The inductance of such a coil isolated from all other objects is[6]

$$(1) \qquad L_o = \mu N^2 (2a - r) \; [(1 - \tfrac{1}{2}k)^2 K(k) - E(k)]$$

Where a = radius of coil
r = radius of wire
μ = permeability of the space surrounding the coil

$$k^2 = \frac{4a(a - r)}{(2a - r)^2}$$

$K(k)$ = complete elliptic integral of the first kind
$E(k)$ = complete elliptic integral of the second kind

This inductance is reduced whenever a conducting plate is brought near the coil. If the axis of the coil is perpendicular to the plate, and the plate is a perfect conductor, the inductance of the coil will be given by

$$(2) \qquad L_c = L_o - \frac{2\,N^2 \mu \sqrt{a(a - r)}}{k_1} \, [(1 - \tfrac{1}{2}k_1^2)\, K(k_1) - E(k_1)]$$

Where $k_1 = \sqrt{\dfrac{4a(a - r)}{(2a - r)^2 + (2d)^2}}$

d = distance between the coil and the metal surface.

Now let it be assumed that the metal plate is of infinite thickness, but of finite conductivity. It is the finite conductivity of the plate which causes a reflected resistance in the coil, and modifies the change in inductance from that given by the above equation. A correction will be added to take this into account.

The first step in finding the resistance reflected into the coil is to obtain an expression for the current density on the surface of the metal assuming perfect conductivity. The usual skin effect resistance (which is derived on the basis of a plane electromagnetic wave on the metal) is multiplied by the square of the current density to obtain the power density. The power density is then integrated over the entire surface of the metal to obtain the total power dissipated. The resistance reflected into the coil is this power divided by the square of the current in the coil.

To obtain a correction for the change of inductance caused by the finite conductivity of the sample, the usual skin effect internal impedance is substituted into the expression for the power dissipated over the whole plane instead of the skin effect resistance alone. When this expression for real and reactive power is divided by the coil current squared, a complex impedance is obtained. The real part of this impedance is taken as the reflected resistance R, and the imaginary part is the correction for the change L_m of inductance caused by the finite conductivity of the metal. The total change L of inductance caused by the proximity of the metal is

$$(3) \qquad L = (L_o - L_c) + L_m$$

where $(L_o - L_c)$ is obtained from (2) and L_m from (13) of the Appendix. By using the skin effect internal impedance for the case of one metal plated on another,[6] one may determine how this type of composite conductor affects the impedance of the coil. The above analysis is subject to the approximations made which are:

1. The current distribution assumed is that for a perfect conductor. This becomes more nearly true as the frequency increases.
2. The usual skin effect internal impedance is derived using the case of a plane wave impinging on the metal. This assumption is more nearly true when the coil is at a great distance from the metal.
3. The idea of substituting the skin effect internal impedance in place of the skin effect resistance is not completely justifiable, but becomes a better approximation as the distance between the coil and metal becomes greater.

However, this analysis does give results over a certain range of coil to sample spacing which are of the correct magnitude, and in certain cases gives very close approximations. The analysis gives successively poor results as the spacing decreases.

III. EXPERIMENTAL WORK

The experimental data was originally taken not as a direct check on the approximate analysis, but as preliminary work with a view toward developing practical instruments for nondestructive tests on metals using the eddy current method. For this reason the probe was not constructed to approximate the idealized coil of the analysis, but was constructed as a practical probe for eddy current testing. Nevertheless, for probe to sample spacings great enough or for the higher frequencies, the probe used to obtain the experimental results included in this paper evidently represents a fair approximation to the idealized coil of the analysis.

Figure 1 shows a plot of the variation of the probe coil inductance L with the metal in proximity, normalized with respect to the inductance L_o with the metal absent. The abscissa is the change R in probe coil resistance normalized with respect to the reactance ωL_o of the coil with the metal absent. The change R is the difference of the probe coil resistance with the metal in proximity and the same resistance with the metal absent. The distance between the probe coil and the metal is indicated in mils on both the theoretical and experimental curves. The divergence between both curves becomes greater as the distance between the probe and metal approaches zero. Figure 2 is the same plot as that of Fig. 1 except that the frequency is six kilocycles per second instead of one kilocycle per second. The agreement between the theoretical and experimental data is much better for the higher frequency or what is the same thing for smaller values of the skin depth.

Figure 3 is a comparison of the theoretical curve for a thick piece of copper at a frequency of six kilocycles per second with the experimental curve for a piece of copper whose thickness is about one-third of the skin depth. Unfortunately the experimental curve for a thick piece of copper was not taken but would lie somewhat below the experimental curve for the one-third skin depth in a similar fashion to that for aluminum in Fig. 2. This seems to indicate that the closer the current is confined to the surface the better is the agreement between experimental and theoretical results. All of these sets of curves diverge

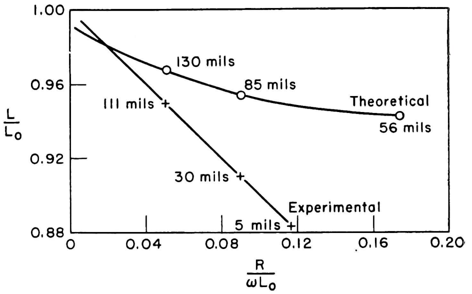
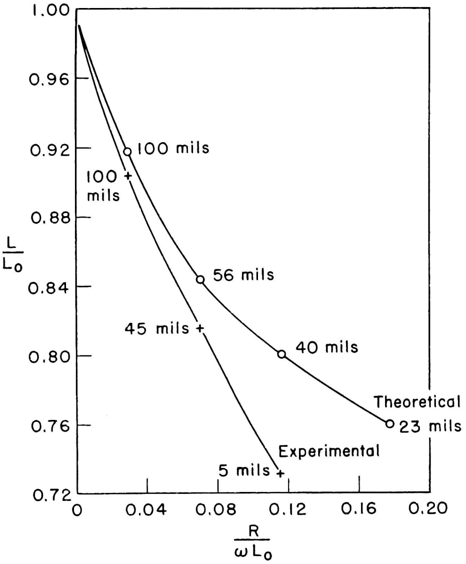


Fig. 1—Variation of the impedance of a probe with spacing in mils for aluminum at a frequency of one kilocycle per second.



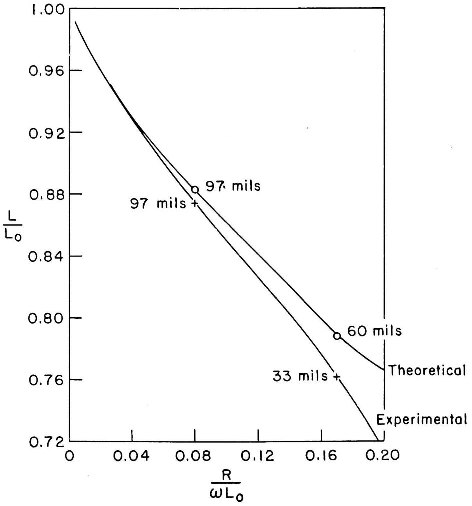


Fig. 2—Variation of the impedance of a probe with spacing in mils for aluminum at a frequency of six kilocycles per second.

Fig. 3—Variation of the impedance of a probe with spacing in mils for a thin piece of copper at a frequency of six kilocycles per second.

as the probe to sample spacing becomes too small. At small spacings, the approximations made in the analysis fail and; also, the probe used on the experiments cannot be regarded as a very good approximation to the ideal coil of the analysis.

Measurements were made using an Owen type a-c bridge constructed of laboratory decade capacitors and resistors. A commercial audio oscillator furnished the low distortion sine wave needed. The probe used consisted of 40 turns of No. 34 wire wound 1/64″ deep and 3/64″ wide on a 1/2″ piece of polystyrene rod. It was necessary to use as small an input voltage as was possible to detect in order to reduce the probe heating to a minimum. Heating of the probe and the consequent change in the probe parameters appears to be one of the major difficulties in the experimental work.

Figure 4 is an experimental plot of the impedance components of a probe placed above 24 St aluminum for different frequencies and different probe-to-

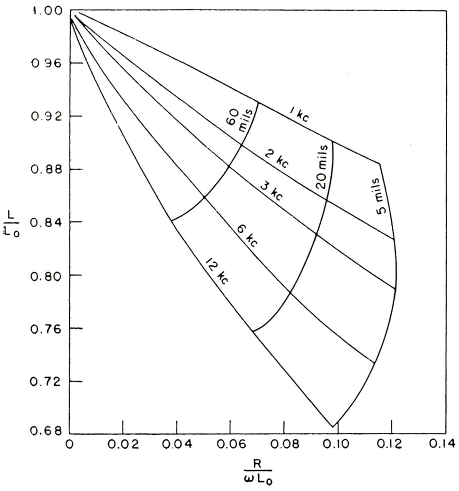


Fig. 4—Impedance plot of a probe for 24 St aluminum with varying frequency and probe-to-metal spacing.

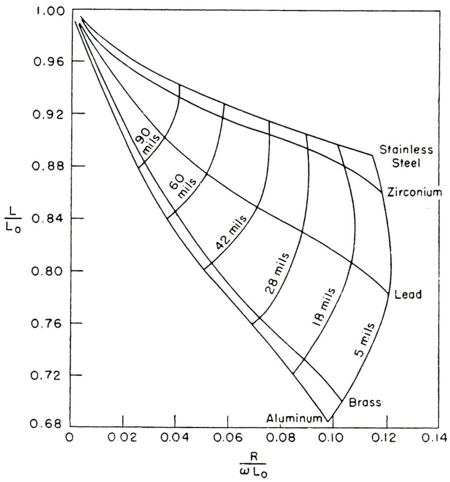


Fig. 5—Impedance plot of a probe at a frequency of 12 KC with varying probe-to-metal spacing and for various metals.

metal spacings. The abscissa is the normalized change in probe resistance $(R/\omega L_o)$, and for a constant probe-to-metal spacing, this normalized change has a maximum value at a certain frequency. For example from Fig. 4 for a 5 mil spacing the maximum value of $(R/\omega L_o)$ occurs between two and three kc. It is also interesting to notice that the change in probe-coil resistance R itself, has a maximum at another higher value of frequency. These maxima can also be obtained from the analysis although the calculations are tedious. The normal depth of penetration of current in the metal is the same at a given frequency regardless of the scale of the coil. Except as noted, these curves are all for samples very thick as compared to this nominal skin depth. According to the analysis, two probes of different sizes but of dimensions proportional to each other should produce the same curves. Experimentally, the two curves do resemble each other but are not quite the same. The explanation seems to be that actual probes have finite dimensions whereas the analysis assumes a vanishingly small diameter of conductor and thickness and width of winding.

As an example of this effect the maxima observed in Fig. 4 do not occur at exactly the same frequency if similarly shaped probes of different dimensions are used. In Fig. 5 the same type of curves are plotted, only this time, the conductivity of the sample rather than the frequency is the parameter.

Since these curves were all taken at the same frequency of 12 kc, the abscissa in this case represents the change in resistance divided by a constant. Notice how R at any given spacing passes through a maximum. For the probe used, this maximum occurred when a metal with a conductivity somewhat poorer than lead was used as a sample. The distances in mils represent the constant probe-to-metal spacing.

In Fig. 6 are plotted the identical curves for brass and zirconium as were plotted in Fig. 5. The small loop between them represents increasing thicknesses in mils of brass shims placed on zirconium, while maintaining a constant probe

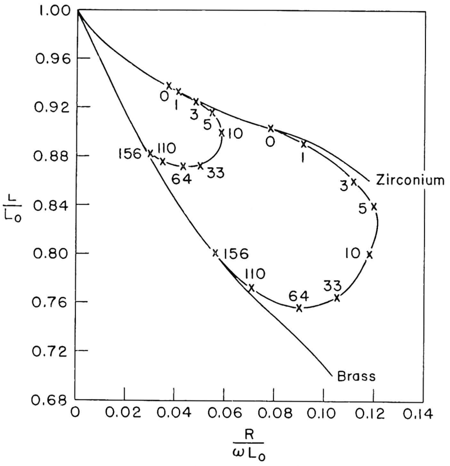


Fig. 6—Impedance plot of a probe at a frequency of 12 KC showing the variation with thickness in mils of brass on a zirconium base.

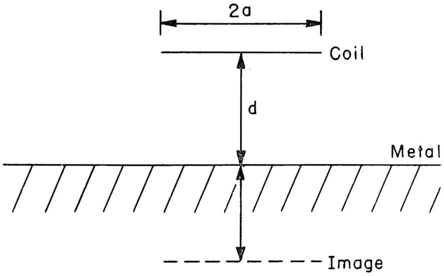


Fig. 7—Geometry of the coil placed near the metal.

to sample spacing. The larger loop represents the same situation except for a smaller probe to sample spacing. The brass shims were pressed firmly against the zirconium, but it is believed that if the brass were plated or clad on the zirconium, the resulting curves would differ slightly from those reproduced because the air layer between the brass and zirconium would disappear. Theoretical curves for the loops were also calculated and were found to have similar shapes except that they did not extend quite as far to the right and also for small thickness of brass, the theoretical curves crossed over the curve for zirconium alone.

IV. CONCLUSIONS

The analytical and experimental results just cited illustrate the variation of the impedance of a probe coil near the surface of a metal. Since the analysis here presented seems to be effective only under certain conditions, what is needed is a more exact analysis which will take into account the coil geometry, as well as the coil to sample spacing, the frequency and the sample conductivity. Once a more exact analysis is made, it will be useful in understanding and applying to practical uses the phenomena noted in this study. It is hoped that the results presented will be useful in the design and development of instruments using probe coils near conducting surfaces.

V. APPENDIX

AN ANALYSIS FOR THE IMPEDANCE OF A COIL NEAR A CONDUCTING SURFACE

For a single coil of N turns isolated from all other objects, the self inductance L_o is given by[6]

$$L_o = \mu N^2(2a - r)\left[1 - \frac{1}{2}k^2\, K(k) - E(k)\right] \tag{4}$$

where a = radius of the coil

r = radius of the wire
μ = permeability of the space surrounding the coil

$$k^2 = \frac{4a(a - r)}{(2a - r)^2}$$

$K(k)$ = complete elliptic integral of the first kind
$E(k)$ = complete elliptic integral of the second kind

When a coil is placed near a perfect conductor as shown in Fig. 7, an image coil coaxial with the first coil may be thought of as existing below the surface of the metal.[7,8] The inductance of the first coil then is

$$(5) \qquad L_c = L_o - \frac{2\mu N^2\sqrt{a(a - r)}}{k_1} [(1 - \tfrac{1}{2}k_1^2)K(k_1) - E(k_1)]$$

where $k_1 = \sqrt{\dfrac{4a(a - r)}{(2a - r)^2 + (2d)^2}}$

d = distance between the coil and the surface of the metal.

The magnetic field intensity on the surface of the metal is

$$(6) \qquad H\rho = \frac{NId}{\pi} \left\{ \frac{\left[\dfrac{a^2 + \rho^2 + d^2}{(a - \rho)^2 + d^2}\right] E(k) - K(k)}{\rho[(a + \rho)^2 + d^2]^{\frac{1}{2}}} \right\}$$

where $k = \sqrt{\dfrac{4a\rho}{(a + \rho)^2 + d^2}}$

I = current in the probe coil

(ρ,ϕ) = polar coordinates on surface of the metal with the origin at the point where the axis of the probe coil meets the surface of the metal. The current density $J\phi$ on the surface of the metal has the same numerical magnitude as the magnetic field intensity $H\rho$ of (5). The power dissipated in the whole plane is

$$P_d = \tfrac{1}{2}\int_o^\infty R_s(2\pi\rho)\, d\rho\, |J\phi|^2$$

$$(7) \qquad = \frac{R_s N^2 I^2 d^2}{\pi} \int_o^\infty \frac{\left\{\left[\dfrac{a^2 + \rho^2 + d^2}{(a - \rho)^2 + d^2}\right] E(k) - K(k)\right\}^2}{\rho[(a + \rho)^2 + d^2]}\, d\rho$$

where R_s = skin resistance of the metal.[6]

The reflected resistance into the coil is

$$(8) \qquad R_r = \frac{P_d}{(I/\sqrt{2})^2} = \frac{2R_s N^2 d^2}{\pi} \int_0^\infty \frac{\left\{\left[\dfrac{a^2 + \rho^2 + d^2}{(a - \rho)^2 + d^2}\right] E(k) - K(k)\right\}^2}{\rho\, [(a + \rho)^2 + d^2)\,]}\, d\rho$$

If now in place of R_s, the skin effect internal impedance

$$(9) \qquad Z_s = R_s + j\, L_i\omega$$

is used, then the impedance Z reflected into the coil is

$$(10) \qquad Z = \frac{2Z_sN^2d^2}{\pi}\int_0^\infty \frac{\left\{\left[\frac{a^2+d^2+\rho^2}{(a-\rho)^2+d^2}\right]E(k)-K(k)\right\}^2}{\rho\left[(a+\rho)^2+d^2\right]}\,d\rho$$

To evaluate the integral of (10) put $x = (\rho/a)$ and $d = (b/a)$ and (10) becomes

$$(11) \qquad Z = \frac{2Z_sN^2b^2}{\pi}\int_0^\infty \frac{\left\{\left[\frac{1+x^2+b^2}{(1-x)^2+b^2}\right]E(k)-K(k)\right\}^2}{x\left[(1+x)^2+b^2\right]}\,dx$$

with $k = \sqrt{\dfrac{4x}{(1+x)^2+b^2}}$

If now in (11) the integration is done with respect to k instead of x, (11) becomes

$$(12) \quad f(y) = \frac{\pi Z}{2Z_sN^2} = \frac{2y}{1+y}\int_0^q \frac{\left\{\left(\frac{1-k^2/2}{1-k^2}\right)E(k)-K(k)\right\}^2}{k\sqrt{\frac{1-k^4\,(1+y)}{(2-k^2)}}}\,dk$$

where $y = b^2$

$$q = \frac{2}{y}\sqrt{(-1+\sqrt{1+y})}$$

The integral $f(y)$ was evaluated on the electronic digital computer AVIDAC at the Argonne National Laboratory with the results given in Table I.

TABLE I

THE FUNCTION $f(y)$ AS EVALUATED BY THE COMPUTER

y	$f(y)$
00.01	15.03865
00.05	05.96961
00.10	03.75141
00.15	02.76572
00.20	02.18480
00.30	01.51567
00.40	01.13766
00.60	00.72687
00.80	00.51158
01.00	00.38193
02.00	00.13857
03.00	00.07164
04.00	00.04381
06.00	00.02131
08.00	00.01254
10.00	00.00831

now let

$$Z = R + j\, L_m \omega \tag{13}$$

where R is the change in resistance of the probe caused by the proximity of the metal and L_m is the change in inductance caused by the fact that the metal is not a perfect conductor. Then the change L in inductance of the probe coil caused by the presence of the metal is

$$L = L_o - (L_c + L_m) = (L_o - L_c) + L_m \tag{14}$$

where $(L_o - L_c)$ may be obtained from (4) and L_m from (11) and (12).

In measuring R and L experimentally, the inductance L_o and the resistance R_o of the probe coil was measured with the metal absent. The metal was then brought close to the coil and the inductance $(L_o + L)$ and the resistance $(R_o + R)$ measured. The difference of the measured quantities gave the change R in resistance and the change L in inductance which could be compared with the calculated values of R and L as obtained from (12) and (13).

It should be pointed out here that the analysis assumes that the frequency is low enough and the probes small enough so that the effect of radiation from the coil may be completely neglected. Also the change in the inductance L_o with frequency is assumed negligible.

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