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A SYSTEM OF GAGING PLATING THICKNESS

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A System for Gaging Plating Thickness

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THE NONDESTRUCTIVE measurement of cladding thickness when the cladding metal and the base metal are nonmagnetic has presented a major problem for a number of years. There have been several different approaches to the problem such as ultrasonics, back scattering of beta or gamma rays, and eddy currents. At present, the eddy-current method appears to have the greatest chance for success. Several eddy-current instruments have been developed, but there is still a need for improved instruments.

This eddy-current method utilized two different techniques in application. The first[1–2] employs sinusoidal eddy currents of a single frequency. This method uses comparatively simple, well-known techniques and instruments, but inaccurate phase measurements and thermal drifts are serious limitations. The second uses pulsed eddy currents containing a spectrum of frequencies. This method uses more complex techniques and instruments, but the phase measurement problem is eliminated, and the thermal problem created by current in the probe coil is minimized.

In the first pulsed eddy-current instrument,[3–5] the cladding thickness was read from the screen of a cathode-ray oscillograph. This instrument suffered from these disadvantages: it was not useful for continuously scanning a metal, and the coating thickness information was presented on the face of an oscilloscope and could not be recorded by a recording voltmeter. A second instrument[6] overcame these difficulties to some extent by the use of photocells placed on the screen of the oscilloscope. It was desirable, however, to eliminate the use of the oscilloscope and photocells if possible, and a new system for transferring the information to a recorder was developed. It is the purpose of this paper to describe this system and to present the results of tests made with it.

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Operation

A small coil near the surface of a metal to be tested established a magnetic field in the metal, and this field induced eddy currents in the metal. The magnitude and direction of the eddy currents depends upon the coil geometry, the coil excitation voltage, the distance from the coil to the metal, and the resistivity of the metal. A change in cladding thickness is a change in resistivity. The impedance of the coil changed with a change in the magnitude and direction of the eddy currents.

A small ferrite-cored coil with its axis perpendicular to the surface of the metal was used to project the field into the metal. The coil windings were concentrated near the end of the probe to obtain maximum sensitivity to a given change in coating thickness. A cross section of the probe is shown in Fig. 1. When the cladding thickness changed, the impedance of the coil changed. To obtain the cladding thickness information, this change in coil impedance was measured with the aid of a bridge circuit.

The bridge circuit in Fig. 2 was excited by discharging a charged capacitor through the thyratron. When the input pulse from the pulse generator triggered the thyratron the 1,000-$\mu\mu$f (micromicrofarad) capacitor discharged through a pulse-shaping network and the primary of the transformer. This provided a bridge excitation pulse shaped like the positive half of a sinusoidal wave. The secondary of the transformer was loosely coupled to the primary and shielded from the primary.

The pulse projected into the coated metal should meet certain length requirements. The length is directly related to the basic time.[3]

$$T=t^2\mu_1\sigma_1$$

where t is the coating thickness. Representative values of T are given in Table I. For best results, the input pulse from the probe should be approximately five times

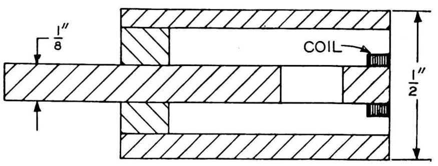

Fig. 1. Probe cross section

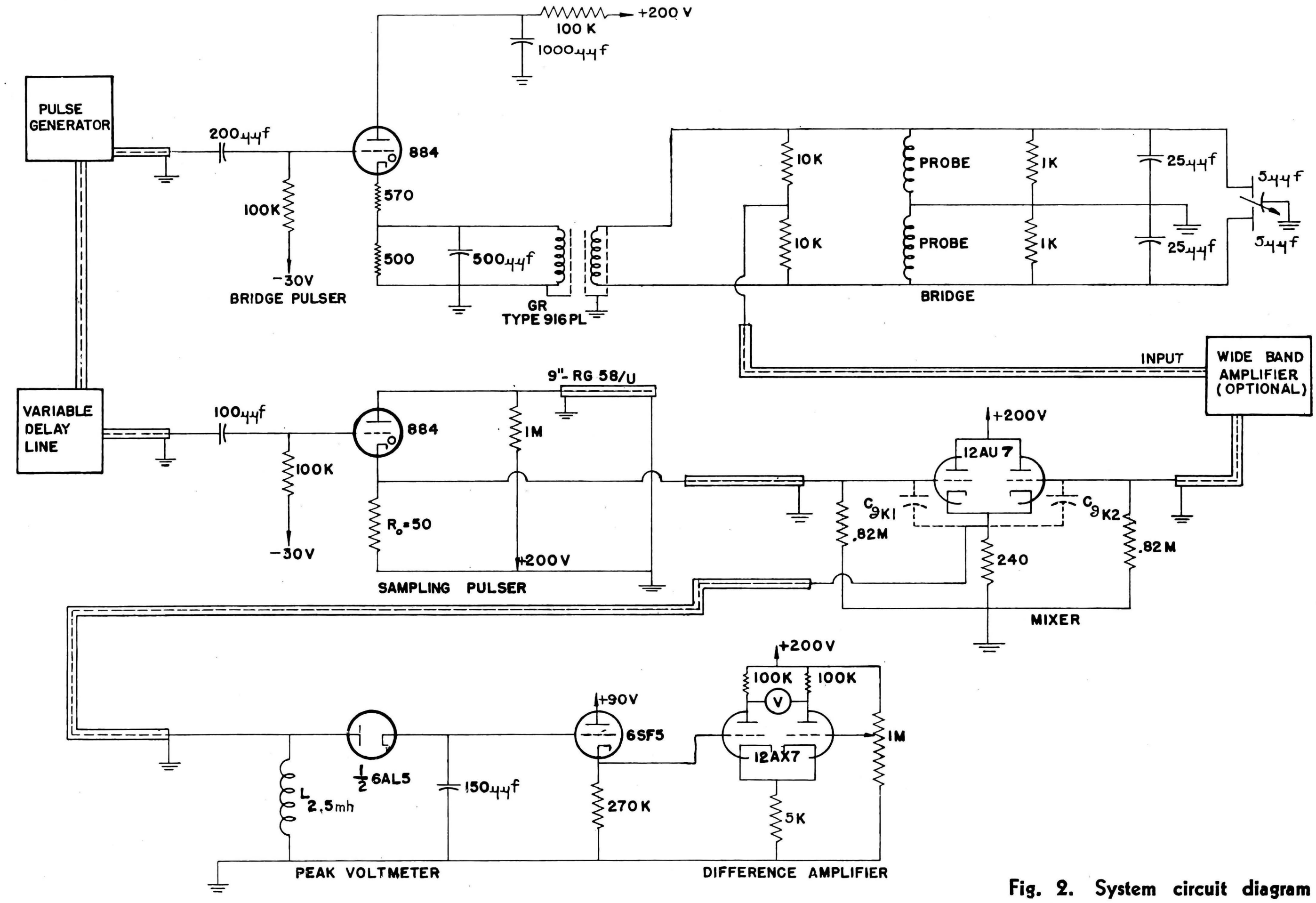

Fig. 2. System circuit diagram

T. From Table I this would necessitate an extreme range of pulse lengths. Some compromise is necessary unless only one coating thickness and coating metal is to be used.

If a slight unbalance is present, an unbalanced voltage exists at the bridge output terminals. A standard sample of metal was placed on one probe, and another sample of metal was placed on the other. Balancing adjustments on the bridge were made, and the bridge output voltage was nearly zero. An unbalance was added by changing the test probe air gap, and the output voltage pulse was as indicated in Fig. 3(A). One major difficulty was variation of the bridge output voltage with probe-to-metal spacing. It was discovered experimentally that one point on the bridge output pulse did not vary in amplitude with the probe-to-metal spacing as indicated in Fig. 3(B). This point will be called the crossing point. The amplitude of the crossing point does vary with the cladding thickness.[6]

Table I. Values of T

Coating Metal	T Microseconds Coating Thickness 5 Mils	25 Mils
Aluminum	0.75	18.8
Zirconium	0.045	1.12
347 stainless steel	28.1	702.0

An analysis of the bridge circuit was made to show that the crossing point does exist. The details of the analysis are given in the Appendix, and the results are shown in Fig. 4, where e_0 is the bridge output voltage and K' is a constant which does not change the shape of the curves. There was one point on the calculated curves that did not vary with the probe-to-metal spacing and this checked with the experimental results indicated in Fig. 3(B).

To determine the cladding thickness, a sample of the bridge output voltage had to be taken at the crossing point. The sampling technique, in other words the technique for separating the probe-to-metal spacing information and the cladding thickness information, will be described in the next two sections.

The Sampling Pulse

To generate a sampling pulse, an *884* thyratron was operated as a switch to discharge a charged transmission line through the characteristic impedance of line as indicated in Fig. 2. The pulse from the bridge circuit and the sampling pulse were synchronized by firing both thyratrons with one pulse generator. The sampling pulse was positioned in time by a variable delay line in the grid circuit of the thyratron.

The duration t_0 of the sampling pulse was calculated from the value of the total storage capacitance C_s and the characteristic impedance R_0 of the line. The network was assumed lossless and was charged to a voltage E. The ampli-

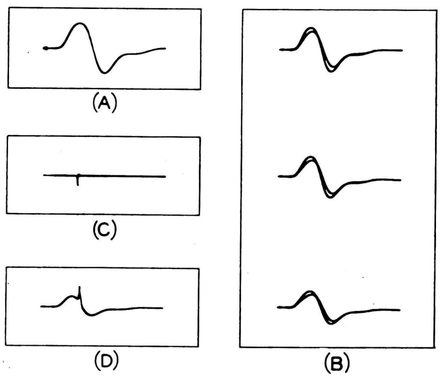

Fig. 3. Waveforms from cathode-ray oscilloscope

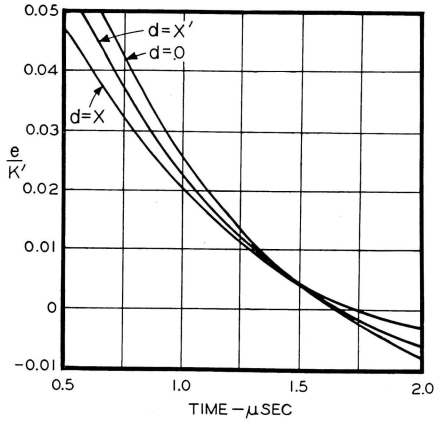

Fig. 4. Calculated bridge output voltage

tude of the pulse was $E/2$. Since the energy originally stored in the capacitance C_s was delivered to the load resistance R_0 during discharge

$$\frac{1}{2}C_sE^2=\left(\frac{E}{2}\right)\left(\frac{E}{2R_0}\right)t_0$$

or $t_0=2R_0C_s$

The duration t_0 for 9 inches of *RG-58/U* coaxial cable was 2.29×10^{-9} second.

The actual pulse shape and length were largely determined by the *884* thyratron. The ionization time was about 10×10^{-9} second and this increased the length of the pulse. The deionization time of the *884* had a very small effect on the pulse length. The transmission line discharged very rapidly, and when the plate voltage dropped to zero, the tube extinguished. Fig. 3(C) shows the sampling pulse. The pulse length was about 15×10^{-9} second and the amplitude was approximately 15 volts.

Mixer and Voltmeter

The mixer in Fig. 2 summed the bridge output pulse and the sampling pulse. The high input impedance reduced the interaction of the two pulses to a minimum. The cathode resistance has to be small to preserve the original waveforms. Much of the energy of the sampling pulse was transferred to the cathode of the mixer through the interelectrode capacitance C_{gk}. The output of the mixer is as indicated in Fig. 3(D).

The sum of the pulse voltage from the bridge circuit at the crossing point and the sampling pulse voltage gave the indication of coating thickness. The peak voltmeter in Fig. 2 measured this sum. During the time of the sampling pulse, a charge built up on the 150-μμf capacitor. During the off part of the cycle the charge decayed at a rate given by the time constant of the capacitance and the input resistance of the *6SF5* triode. Since the input resistance of the *6SF5* was very large, the time constant for the decay was very large, and the charge on this capacitor decayed very slowly. As a result, the peak of the sampling pulse was measured with no interference from the peak of the bridge output pulse. The difference amplifier in Fig. 2 provided a high gain and a simple method for balancing out the direct voltage that contained no coating thickness information. With a proper selection of voltmeter, the coating thickness can be read directly in mils. The results for nonmagnetic stainless-steel-coated on brass are given graphically in Fig. 5 where d is the probe-to-metal spacing. It should be noticed that the readings are nearly independent of the probe-to-metal spacing.

One difficulty experienced was a seemingly random variation in the output indication. The use of regulated power supplies helped this considerably, but there was still a small amount of the random variation left. It is probable that further work on the supplies would eliminate most of this difficulty.

Conclusions

The calculated bridge output voltage indicated the presence of the crossing point. The major error in the calculation was introduced by the probe characteristic assumptions. A true equivalent circuit for the probe has not been found, and this will have to be done before exact calculations can be made.

This eddy-current instrument measures cladding thickness fairly independent of probe-to-metal spacing. Pulsed eddy currents have one major advantage over sinusoidal eddy currents: a much higher peak current can be applied to the probe coil without heating the coil if the proper pulse length and repetition rate have been selected. The one major disadvantage of this pulse system is that the pulses must be very stable in amplitude and time.

Appendix

Bridge Circuit Analysis

The equivalent circuit of the bridge circuit and bridge circuit pulser is shown in Fig. 6(A). The voltage e was calculated by replacing the transformer and the bridge with an equivalent circuit which was found by measuring the input impedance at the transformer primary. Then the equivalent circuit is as shown in Fig. 6(B).

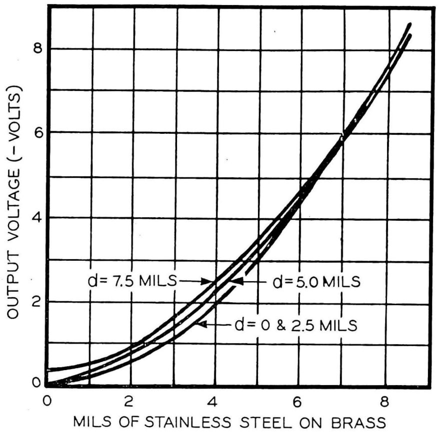

Fig. 5. Output of entire system

The expression for the Laplace transform of the voltage e is

$$\mathfrak{L}(e)=\frac{\left(\frac{1}{R_1C'}\right)E_0S}{S^3+\left(\frac{1}{R_1C}+\frac{1}{R'C'}+\frac{1}{R_1C'}\right)S^2+\left(\frac{1}{R_1R'CC'}+\frac{1}{C'L'}\right)S+\frac{1}{R_1CC'L'}} \quad (1)$$

Substituting circuit values

$$\mathfrak{L}(e)=\frac{3.46\times10^6\,E_0S}{S^3+9.15\times10^6S^2+12.76\times10^{12}S+9.35\times10^{18}} \quad (2)$$

The Laplace transform of the primary current is

$$\mathfrak{L}(i_p)=\frac{1}{L'S}\,\mathfrak{L}(e) \quad (3)$$

After substituting equation 2 into equation 3 and taking the inverse Laplace transform, the primary current i_p is

$$i_p=1.67\times10^{-3}E_0\epsilon^{-0.755\times10^6t}\times\sin(0.806\times10^6t-6.8°) \quad (4)$$

for $t\geqq0.3$ μsec (microsecond). The Laplace transform for the approximate primary current i_p is:

$$\mathfrak{L}(i_p)=\frac{-0.197\times10^{-3}E_0S+1.19\times10^3E_0}{[(S+0.755\times10^6)^2+(0.806\times10^6)]^2} \quad (5)$$

The resistances R_1 and R_2 were assumed small enough to be neglected. The 10-kilohm resistances may be neglected, because they are large compared to the 1-kilohm resistances. The large input resistance R_d of the mixer was neglected.

With the bridge balanced, the voltage equation for the secondary is

$$0=M\frac{di_p}{dt}+L_s\frac{di_2}{dt}+i_2Z \quad (6)$$

where Z is the entire bridge impedance, and

$$Z(s)=\frac{2LRS}{RCLS^2+LS+R} \quad (7)$$

The Laplace transform of equation 6 was solved for the Laplace transform of the

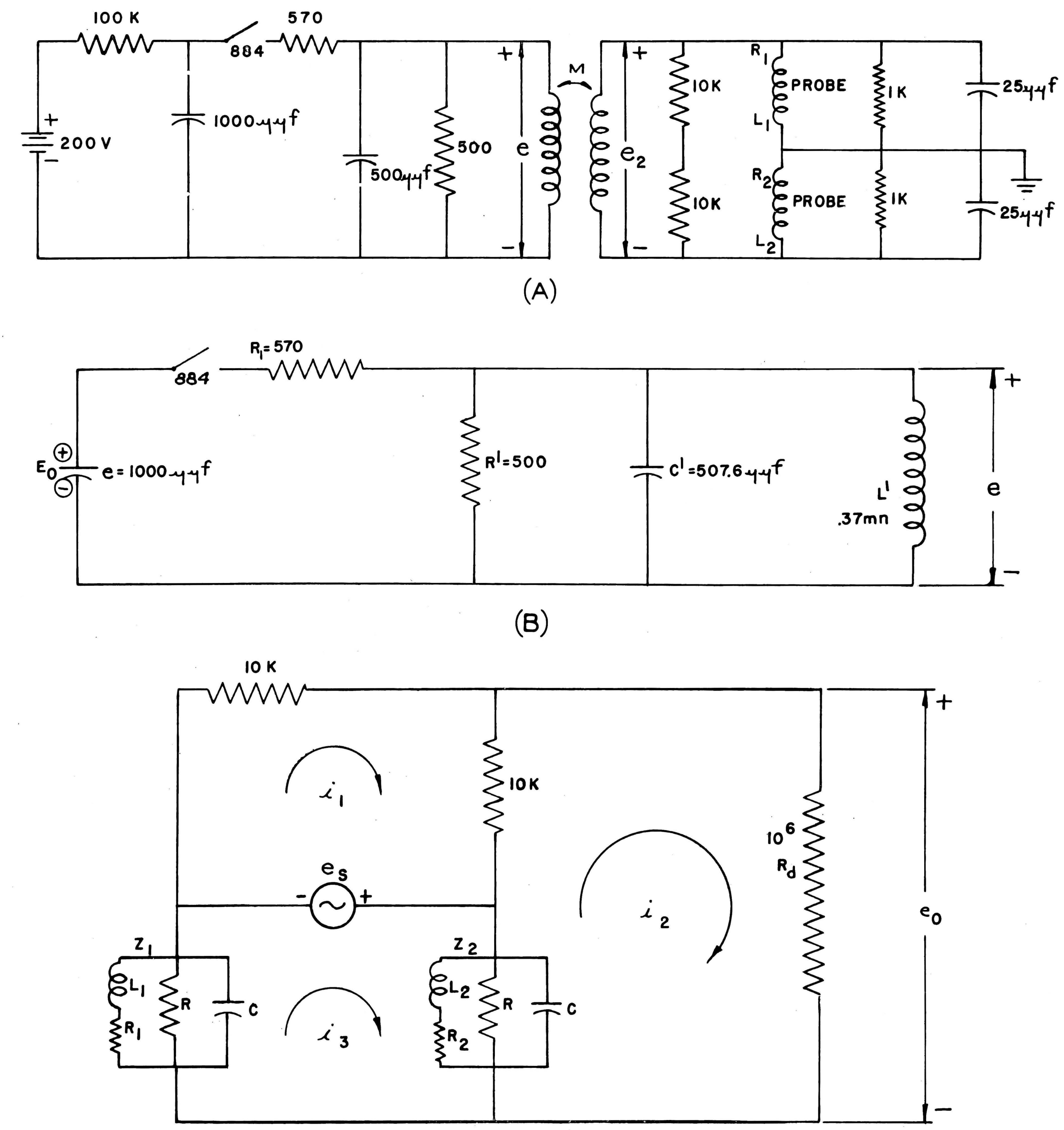

Fig. 6. Equivalent circuit

A—Of bridge pulser and bridge
B—For calculating voltage across transformer primary
C—Of the bridge

secondary current. Multiply by $Z(s)$ to obtain

$$\mathfrak{L}(e_2) = \frac{-MS\mathfrak{L}(i_p)Z(s)}{L_sS+Z(s)} \tag{8}$$

The circuit values were substituted in equation 5 and the inverse Laplace transform was used to obtain

$$\frac{e_2}{K10^{-9}} = 9.8\epsilon^{-0.755\times10^6t}\sin(0.806\times10^6t+ 46.6°)+88^{-8.45\times10^6t}- 1630^{-31.6\times10^6t} \tag{9}$$

where

$$K=0.394\times10^{-3}\frac{ME_0}{L_sC}$$

This equation is approximated by

$$\frac{e_2}{K10^{-9}}=45\epsilon^{-0.9\times10^6t} \tag{10}$$

or 0.5 μsec$\leq t \leq$2.0 μsec. The Laplace transform of equation 10 is

$$\frac{\mathfrak{L}(e_2)}{K10^{-9}}=\frac{45}{S+0.9\times10^6} \tag{11}$$

The bridge circuit was drawn as indicated in Fig. 6(C). Let the voltage e_s be any applied voltage, and e_0 the output voltage. The mixer input resistance was assumed to be 10^6 ohms. The loop equations were

$$-e_s = 20\times10^3 i_1 - 10\times10^3 i_2 \qquad (12)$$

$$0 = -10^4 i_1 + (10^4 + 10^6 + Z_2) i_2 - Z_2 i_3 \qquad (13)$$

$$e_s = -Z_2 i_2 + (Z_1 + Z_2) i_3 \qquad (14)$$

These equations were solved for the current i_2, and i_2 was multiplied by the mixer input resistance to obtain

$$e_0 = \frac{10^6 (Z_2 - Z_1) e_s}{2Z_1Z_2 + 2.01\times10^6 (Z_1 + Z_2)} \qquad (15)$$

The Laplace transform of this equation is

$$\mathcal{L}(e_0) = \frac{10^6 [Z_2(s) - Z_1(s)] \mathcal{L}(e_s)}{2Z_1(s)Z_2(s) + 2.01\times10^6 [Z_1(s) + Z_2(s)]} \qquad (16)$$

where

$$Z_t(s) = \frac{\frac{1}{C} S + \frac{R_t}{L_t}}{S^2 + \frac{R_t}{L_t} + \frac{1}{RC} S + \frac{R_t + R}{CL_t}} \qquad (17)$$

The probe characteristics are assumed to be $L_0 = 200$ microhenrys, and $R_0 = 50$ ohms in air. From previous sinusoidal investigations,[1] the probe inductance and resistance varied with a change in probe-to-metal spacing according to $L = L_0 - \Delta L$, and $R = R_0 + \Delta R$, where $\Delta R = K\Delta L$ and K is a constant.

Let L_1 and R_1 equal L_0 and R_0 respectively. Let it be assumed that a metal is close to probe 2, and that the probe characteristics for three different probe-to-metal spacings are as follows:

d	L_2(μh)	R_2(Ω)
0	120	80
X′	130	75
X	140	70

These values were substituted in equations 16 and 17. Let equation 11 be the applied voltage function. This was substituted in equation 16 in place of the Laplace transform of any voltage function e_s. The inverse Laplace transform was taken and for $d=0$,

$$\frac{e_0}{K'} = -0.105\epsilon^{-0.403\times10^6 t} + 0.236\epsilon^{-0.9\times10^6 t} \qquad (18)$$

where $K' = \frac{-45}{K10^{-9}}$

for $d = X'$

$$\frac{e_0}{K'} = -0.081\epsilon^{-0.378\times10^6 t} + 0.192\epsilon^{-19\times10^6 t} \qquad (19)$$

for $d = X$

$$\frac{e_0}{K'} = -0.059\epsilon^{-0.852\times10^6 t} + 0.151\epsilon^{-0.9\times10^6 t} \qquad (20)$$

These equations are plotted in Fig. 4.

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