THE ANALYSIS OF REFLECTION TYPE COILS FOR EDDY-CURRENT TESTING

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C. V. Dodd, C. C. Cheng,[1] W. A. Simpson, D. A. Deeds,[2] and J. H. Smith

ABSTRACT

This report contains the theoretical analysis and computer programs for reflection type coils above multiple layered conductors. The performance of the coils when connected to phase-sensitive eddy-current instrumentation can be evaluated. The programs are written in both BASIC and FORTRAN for timesharing on the PDP-10 to calculate the effects of defects or variations in either conductivity or thickness for multiple conductors, all in the presence of lift-off variations. In addition, program options are included that allow the study of the design of the coil, the effects of small variations or drifts of all the coil, conductor and instrument parameters, and the effects of the instrument output and input impedance on the problem. Examples are given of the use of the programs for the design of eddy-current tests with reflection type coils. Application of these techniques allow optimum design of eddy-current tests using probe coils without the necessity of expensive trial and error experiments and fabrication. These programs can be applied to the solution of many inspection problems involving reactor fuels and materials.

INTRODUCTION

Eddy-current tests have been successfully used for many years in industry to measure the thickness of conductors, to measure the electrical conductivity or magnetic permeability of metals, to detect defects in metals and to measure the distance between conducting components. Early eddy-current instruments used simple bridge circuits operated in a balanced mode and measured the magnitude of the signal as the balance changed. Later instruments used bridges with a test coil and a reference coil operated in an unbalanced mode to measure the effect of one variable and eliminate the effects of all the other variables. These instruments may measure either magnitude or phase of the bridge unbalance

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[2]Summer student from the University of Tennessee.

voltage.[3,4] Still later instruments use bridges with transformer coupling from a primary into a secondary which is connected to the test and reference coils. Instruments developed at Oak Ridge National Laboratory[5,6] utilize a reflection type probe, as shown in Fig. 1. This probe consists of a large driver coil to generate the electromagnetic field and two pickup coils, connected in a differential arrangement to measure differences in this field. In air, the signals developed across the pickup coils cancel due to the symmetry of the field, but when a conductor is present the field is unbalanced and a signal results. The total field in the presence of a metal can be considered as the sum of the original field of the coil in air, plus a reflected field. The original field of the coil in air is still symmetrical with respect to the pickups and cancels, but the reflected field is much larger at the front pickup (nearest the metal) than at the rear pickup coil and does not cancel. Thus, the signal produced by the pickup coils is approximately equal to the reflected field. This arrangement is approximately equivalent to a bridge circuit with a test and reference coil having transformer coupling directly from the primary (driver) coil to the test and reference (front and rear pickup) coils.

The magnitude of the reflected signal is a function of lift-off (coil to conductor spacing), electrical conductivity, magnetic permeability, the thickness of the conductor and the presence of discontinuities in the conductor. The phase of the reflected signal is also a function of the same parameters but does not vary nearly as much with lift-off as the magnitude.

This report is devoted to the analysis, computer calculation and design of reflection coils and their associated circuitry. The programs

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[3] R. Hochschild, "Electromagnetic Methods of Testing Metals," *Progress in Nondestructive Testing*, Vol. I, The Macmillan Company, New York, 1959.

[4] R. C. McMaster, *Nondestructive Testing Handbook*, Vol. II, The Ronald Press Co., 1959.

[5] C. V. Dodd, "Applications of a Phase-Sensitive Eddy-Current Instrument," *Mater. Eval.* 22(6): 260–63 (June 1964).

[6] C. V. Dodd, "A Portable Phase-Sensitive Eddy-Current Instrument," *Mater. Eval.* 26(3): 33–36 (March 1968).

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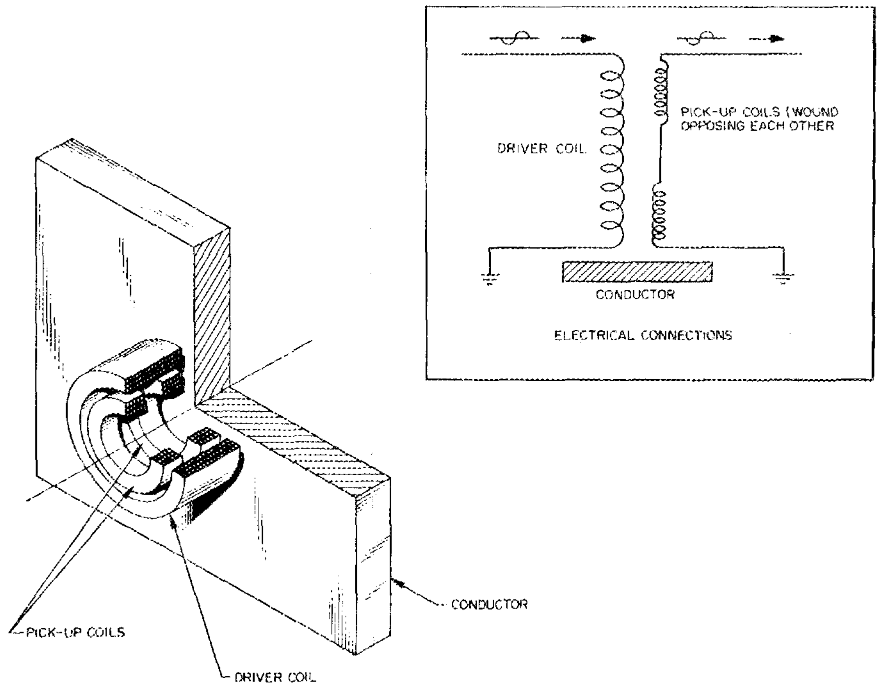
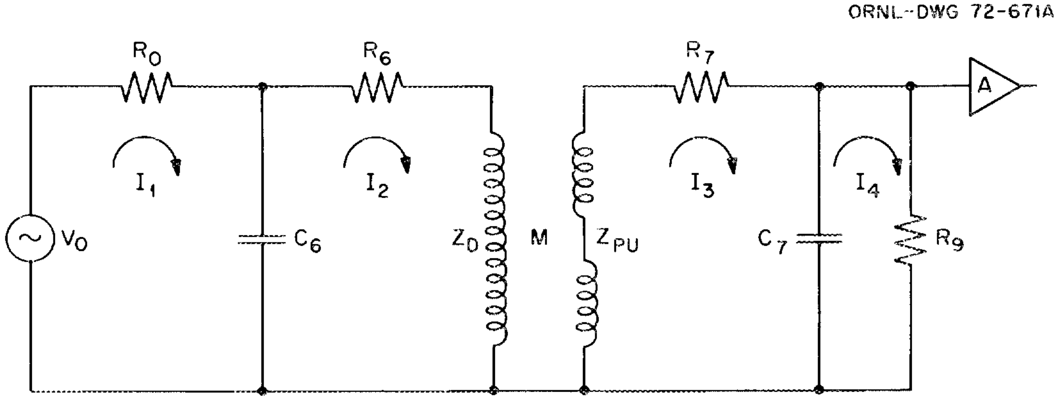


Fig. 1. A Reflection-Type Probe in the Presence of a Conductor.

will calculate the actual phase and magnitude of the reflected signals when the probes are connected to phase-sensitive eddy-current instrumentation developed at Oak Ridge National Laboratory. Each program is self-contained and will allow the complete design of an entire system for conductivity measurements, thickness measurements etc., including the coil, attenuation, and operating parameters.

THEORETICAL ANALYSIS

The equivalent circuit of a reflection type probe is shown in Fig. 2. We can write the following set of equations for the drops in voltage around each of the loops in the circuit:



V_0 DRIVING VOLTAGE
R_0 SERIES RESISTANCE IN THE DRIVING CIRCUIT
C_6 SHUNT CAPACITANCE OF THE DRIVING CIRCUIT
R_6 D.C. RESISTANCE OF THE DRIVER COIL
Z_D IMPEDANCE OF THE DRIVER COIL
M MUTUAL IMPEDANCE BETWEEN THE DRIVER AND PICK-UP COILS
Z_{PU} IMPEDANCE OF THE PICK-UP COILS
R_7 D.C. RESISTANCE OF THE PICK-UP COILS
C_7 SHUNT CAPACITANCE OF THE PICK-UP CIRCUIT
R_9 AMPLIFIER INPUT IMPEDANCE
I LOOP CURRENT

Fig. 2. Simplified Circuit Diagram for an Eddy-Current Reflection Type Probe.

$$I_1\left(R_0 - \frac{j}{\omega C_6}\right) - I_2\left(-\frac{j}{\omega C_6}\right) = V_0 \quad (1)$$

$$-I_1\left(-\frac{j}{\omega C_6}\right) + I_2\left(-\frac{j}{\omega C_6} + R_6 + Z_D\right) - I_3(j\omega M) = 0 \quad (2)$$

$$-I_2(j\omega M) + I_3\left(Z_{PU} + R_7 - \frac{j}{\omega C_7}\right) - I_4\left(-\frac{j}{\omega C_7}\right) = 0 \quad (3)$$

$$-I_3\left(-\frac{j}{\omega C_7}\right) + I_4\left(-\frac{j}{\omega C_7} + R_9\right) = 0 \quad (4)$$

where j is the square root of −1 and ω is the angular operating frequency.

We can use determinants and solve for the current in the final loop, I_4, produced by an applied voltage V_0:

$$I_4 = \frac{\begin{vmatrix} R_o - \frac{j}{\omega C_6} & \frac{j}{\omega C_6} & 0 & V_0 \\ \frac{j}{\omega C_6} & \frac{-j}{\omega C_6} + R_6 + Z_D & -j\omega M & 0 \\ 0 & -j\omega M & Z_{PU} + R_7 - \frac{j}{\omega C_7} & 0 \\ 0 & 0 & \frac{j}{\omega C_7} & 0 \end{vmatrix}}{\begin{vmatrix} R_o - \frac{j}{\omega C_6} & \frac{j}{\omega C_6} & 0 & 0 \\ \frac{j}{\omega C_6} & \frac{-j}{\omega C_6} + R_6 + Z_D & -j\omega M & 0 \\ 0 & -j\omega M & Z_{PU} + R_7 - \frac{j}{\omega C_7} & \frac{j}{\omega C_7} \\ 0 & 0 & \frac{j}{\omega C_7} & \frac{-j}{\omega C_7} + R_9 \end{vmatrix}} \qquad (5)$$

We shall solve for the current, I_4, multiply it by the resistance R_9 to determine the input voltage to the amplifier and then multiply by the amplifier gain G to determine the voltage output.

$$V_{out} = -j\,\frac{MV_0R_9G}{\omega C_6C_7} \div \left\{\left(R_o - \frac{j}{\omega C_6}\right)\omega^2M^2\left(R_9 - \frac{j}{\omega C_7}\right)\right. \qquad (6)$$

$$\left. + \left[\left(R_o - \frac{j}{\omega C_6}\right)\left(Z_D + R_6 - \frac{j}{\omega C_6}\right) + \frac{1}{\omega^2C_6^2}\right]\left[\left(R_9 - \frac{j}{\omega C_7}\right)\left(Z_{PU} + R_7 - \frac{j}{\omega C_7}\right) + \frac{1}{\omega^2C_7^2}\right]\right\}$$

From Eq. (6) we can calculate the phase shift between the voltage driving the eddy-current probe and the amplified voltage received at the phase shift detector. All the terms in Eq. (6) can easily be determined except for the mutual impedance between the driver and pickup coils, M, the driver coil impedance, Z_D, and the pickup coil impedance, Z_{PU}.

We can derive the following expression[7] for the voltage induced in a pickup coil by a current I_1 flowing in a driver coil, as shown in Fig. 3.

$$V = j\omega I_1 \pi n n' \mu_0 \int_0^\infty \frac{1}{\alpha^6} J(r_2,r_1) J(r_4,r_3) \Big\{ 2\alpha(\ell_2' - \ell_1') + \left[1 - e^{-\alpha(\ell_2'-\ell_1')}\right] \cdot \left[\gamma \left(e^{-\alpha(\ell_1+\ell_1')} - e^{-\alpha(\ell_2+\ell_1')}\right) - e^{-\alpha(\ell_2-\ell_2')} - e^{-\alpha(\ell_1'-\ell_1)}\right] \Big\} d\alpha \quad (7)$$

The driver coil has n turns per unit cross-sectional area; the pickup coil has n' turns per unit cross-sectional area and must not extend beyond the driver in the axial direction (ℓ_2' must not be greater than ℓ_2 and ℓ_1' must not be less than ℓ_1). The γ factor is a function of the metal alone and is more fully explained in ref. 7. The function $J(r_2,r_1)$ is

$$\int_{\alpha r_1}^{\alpha r_2} x\, J_1(x)\, dx ,$$

where $J_1(x)$ is a first order Bessel function.

We shall now add a second pickup coil to the probe in Fig. 3, but with the turns reversed, as shown in Fig. 4. The equation for the second pickup will be the same as Eq. (7), except the sign will be reversed. This is equivalent to integrating the vector potential in the positive Θ direction for one coil and the negative Θ direction for the other coil. We shall take the direction of the turns in the front pickup coil (nearest the metal) to be the same as the driver, and the turns of the rear pickup coil to be in a direction opposite the driver. This reversal of turns in the rear pickup will give a negative sign when the integration around the coil is performed. We will then have for the total mutual coupling between the driver and both pickups

[7] C. C. Cheng, C. V. Dodd, and W. E. Deeds, "General Analysis of Probe Coils Near Stratified Conductors," *Int. J. Nondestruct. Test.* 3: 109–30 (1971).

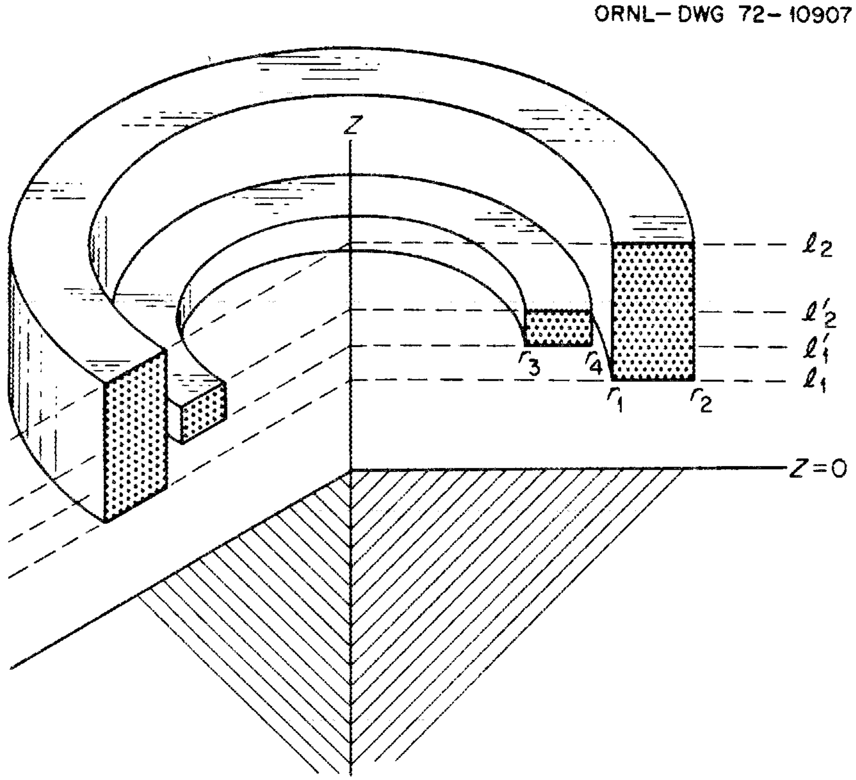


Fig. 3. Driver Coil Encircling a Pickup Coil.

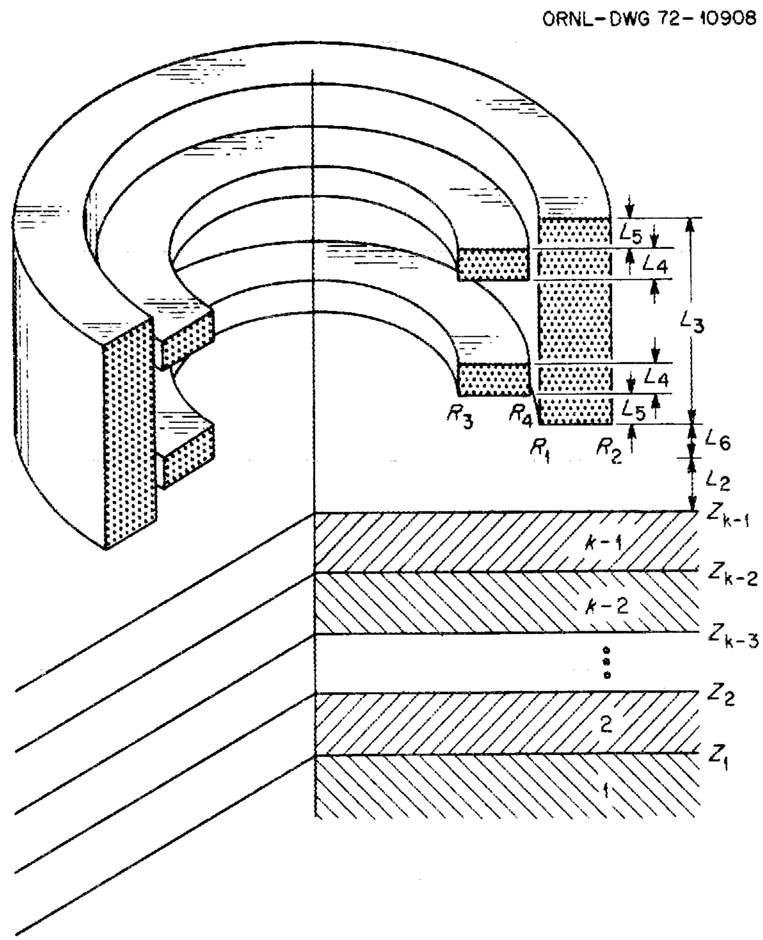


Fig. 4. Reflection Probe Above Multiple Conductors.

$$M = \frac{1}{j\omega I}\left\{V(\text{driver, front pickup}) + V(\text{driver, rear pickup})\right\}$$

where V is given by substituting the proper dimensions in Fig. 4 into Eq. (7), with a negative sign for the rear pickup. The results are

$$M = \frac{\pi N_3 N_4 \mu_0 \; R_5}{L_3(R_2-R_1)L_4(R_4-R_3)} \int_0^\infty \frac{1}{\alpha^6} J(R_2,R_1)J(R_4,R_3)\; e^{-\alpha L_5} e^{-2\alpha L_2} e^{-2\alpha L_6}$$

$$\left(1 - e^{-\alpha L_4}\right)\left(1 - e^{-\alpha L_3}\right)\left(1 - e^{-\alpha(L_3-L_4-2L_5)}\right) \gamma d\alpha \qquad (8)$$

where

L_6 = the minimum amount of lift-off of the driver coil,

L_2 = the increase in lift-off,

L_3 = the length of the driver coil,

L_4 = the length of each pickup coil,

L_5 = the distance each pickup is recessed from each end of the driver coil,

N_3 = the number of turns on the driver coil,

N_4 = the number of turns on each pickup coil,

R_1 = the driver coil inner radius,

R_2 = the driver coil outer radius,

R_3 = the pickup coil inner radius,

R_4 = the pickup coil outer radius, and

R_5 = the mean radius of the driver coil.

All dimensions have been normalized in Eq. (8) by dividing by the mean radius of the driver coil, and all the α's have been multiplied by the same mean radius.

The impedance of the driver coil, Z_D, can be calculated from Eq. (7) by making both coils the same and dividing by I_1. The results are

$$Z_D = \frac{j\omega\pi\mu_0 N_3{}^2 R_5}{(R_2-R_1)^2 L_3{}^2} \int_0^\infty \frac{1}{\alpha^6} J^2(R_2,R_1) \left\{ 2\left[\alpha L_3 + e^{-\alpha L_3} - 1\right] + \left[1 - e^{-\alpha L_3}\right]^2 e^{-2\alpha L_2} e^{-2\alpha L_6} \gamma \right\} d\alpha \quad . \tag{9}$$

We shall now calculate the total coil impedance of the two pickup coils. The total vector potential produced by a current flowing in the pickup coils is

$$\vec{A}_{PU} = \vec{A}_{PU_1} - \vec{A}_{PU_2} \quad . \tag{10}$$

We have made the vector potential from the front pickup coil (PU_1) in Fig. 4 positive and therefore the second pickup (PU_2) negative due to its current flowing in the opposite direction. If we open the driver circuit (make R_0 infinite and V_0 and C_6 zero), we will have no current flow in the driver coil and no contribution to the vector potential from the driver coil. In the actual circuit, the entire interaction between the driver and pickup coils is contained in the mutual impedance term.

The total self-induced voltage in the pickups is

$$V_{PU} = j\omega\oint \vec{A}_{PU} \cdot d\vec{\ell}_{PU} = j\omega\oint \left\{ \vec{A}_{PU_1} \cdot d\vec{\ell}_1 - \vec{A}_{PU_2} \cdot d\vec{\ell}_1 + \vec{A}_{PU_1} \cdot d\vec{\ell}_2 - \vec{A}_{PU_2} \cdot d\vec{\ell}_2 \right\} . \tag{11}$$

However $\vec{\ell}_2$ is in the opposite direction from our normal direction of integration. Performing the dot product and integrating in the $+\Theta$ direction gives:

$$V_{PU} = j\omega \oint \left\{ A_{PU_1} d\ell_1 + A_{PU_2} d\ell_2 - A_{PU_2} d\ell_1 - A_{PU_1} d\ell_2 \right\} . \tag{12}$$

Calculating the impedance of both coils gives

$$Z_{PU} = \frac{V_{PU}}{I} = \frac{j\omega}{I}\oint A_{PU_1}\,d\ell_1 + \frac{j\omega}{I}\oint A_{PU_2}\,d\ell_2 - \frac{j\omega}{I}\oint A_{PU_2}\,d\ell_1 - \frac{j\omega}{I}\oint A_{PU_1}\,d\ell_2 \quad .$$

This equation is the same as

$$Z_{PU} = Z_{PU_1} + Z_{PU_2} - 2j\omega M_{12} \tag{13}$$

which can be obtained by considering the coils separately. From ref. 7, Eq. (57), we can write the following relationship for the voltage induced in the upper pickup coil by a current in the lower pickup coil,

$$j\omega M_{12} = \frac{j\omega\pi N_4{}^2 R_5 \mu_0}{(R_4-R_3)^2 L_4{}^2}\int_0^\infty \frac{1}{\alpha^6}\, J^2(R_4,R_3)\left[\gamma e^{-\alpha(2L_2+2L_6+L_3-L_4)} + e^{-\alpha(L_3-2L_4-2L_5)}\right]\left(1 - e^{-\alpha L_4}\right)^2 d\alpha \quad . \tag{14}$$

From ref. 7, Eq. (58), we can write the same expression for the voltage induced in the lower pickup coil by a unit current in the upper pickup coil.

Using Eq. (7) for the impedance of the front pickup coil gives

$$Z_{PU_1} = \frac{j\omega\pi N_4{}^2 \mu_0 R_5}{(R_4-R_3)^2 L_4{}^2}\int_0^\infty \frac{1}{\alpha^6}\, J^2(R_4,R_3)\left\{2\left(\alpha L_4 + e^{-\alpha L_4} - 1\right) + \left(1 - e^{-\alpha L_4}\right)^2 \gamma e^{-\alpha(2L_5+2L_6+2L_2)}\right\} d\alpha \quad . \tag{15}$$

For the rear pickup we have

$$Z_{PU_2} = \frac{j\omega\pi N_4{}^2\mu_0 R_5}{(R_4-R_3)^2 L_4{}^2} \int_0^\infty \frac{1}{\alpha^6} J^2(R_4,R_3) \left\{ 2\left(\alpha L_4 + e^{-\alpha L_4} - 1\right) + \left(1 - e^{-\alpha L_4}\right)^2 \gamma e^{-\alpha(2L_6 + 2L_2 + 2L_3 - 2L_5 - 2L_4)} \right\} d\alpha \quad . \tag{16}$$

From Eq. (13) the total pickup coil impedance is the sum of Eqs. (15) and (16) minus twice Eq. (14). The result is

$$Z_{PU} = \frac{j\omega\pi N_4{}^2\mu_0 R_5}{(R_4-R_3)^2 L_4{}^2} \int_0^\infty \frac{1}{\alpha^6} J^2(R_4,R_3) \left\{ 4\left(\alpha L_4 + e^{-\alpha L_4} - 1\right) + \left(1 - e^{-\alpha L_4}\right)^2 \left[e^{-\alpha(2L_2+2L_6+2L_5)}\left(1 - e^{-\alpha(L_3-L_4-2L_5)}\right)^2 \gamma - 2e^{-\alpha(L_3-2L_4-2L_5)} \right] \right\} d\alpha \quad . \tag{17}$$

We have now derived equations for the mutual impedance between the driver and pickup coils, M, the driver coil impedance, Z_D, and the pickup coil impedance, Z_{PU}, and only these factors are needed for thickness, cladding thickness, and conductivity calculations. However, if we wish to calculate the effect of discontinuities, we must go still further. The quantities that we have already calculated will be modified slightly due to the presence of a flaw in the material.

The voltage change in the driver coil[8] per unit current in a pickup coil due to the presence of a flaw is:

$$\frac{V_d}{I_D} = \left[\frac{3}{2}\sigma\omega^2\left(\frac{A_{PU}}{I_{PU}}\right)\left(\frac{A_D}{I_D}\right)\right] \times \left[\text{Vol } \alpha_{22}\right] = j\omega M' \quad , \tag{18}$$

where A_{PU} and A_D are the vector potentials of the driver and pickup coils, respectively. The factor [Vol α_{22}] is a size, shape, and

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[8]C. V. Dodd, W. E. Deeds, J. W. Luquire, and W. G. Spoeri, *Some Eddy-Current Problems and Their Integral Solutions*, ORNL-4384 (April 1969).

orientation factor and will be discussed later. The vector potential for any region, n, below the coil, from ref. 7, Eq. (55) is

$$A^{(n)}(r,z) = \frac{1}{2}\frac{NI\mu_0}{(r_2-r_1)(\ell_2-\ell_1)} \int_0^\infty \frac{e^{-\alpha\ell_1}}{\alpha^3} J(r_2,r_1)\left[1 - e^{-\alpha(\ell_2-\ell_1)}\right] \times J_1(\alpha r)\left\{\frac{V_{12}(n,1)}{V_{22}(k,1)} e^{-\alpha_n z} + \frac{V_{22}(n,1)}{V_{22}(k,1)} e^{\alpha_n z}\right\} d\alpha \quad . \tag{19}$$

Substituting for the vector potential of the driver and pickup coils in Eq. (18) gives

$$\frac{V_d}{I} = \text{Vol } \alpha_{22} \frac{3}{8} \frac{\sigma_n \omega^2 N_4 N_3 \mu_0^2}{(R_2-R_1)(R_4-R_3)L_4L_3} \left\{\int_0^\infty \frac{e^{-\alpha(L_2+L_6)}}{\alpha^3} J(R_2,R_1)\left(1 - e^{-\alpha L_3}\right) \times J_1(\alpha r)\left[\frac{V_{12}(n,1)}{V_{22}(k,1)} e^{-\alpha_n z} + \frac{V_{22}(n,1)}{V_{22}(k,1)} e^{\alpha_n z}\right] d\alpha\right\}$$
$$\times \left\{\int_0^\infty \frac{e^{-\alpha(L_2+L_6+L_5)}}{\alpha^3}\left(1 - e^{-\alpha(L_3-L_4-2L_5)}\right) J(R_4,R_3)\left(1 - e^{-\alpha L_4}\right) \times J_1(\alpha r)\left[\frac{V_{12}(n,1)}{V_{22}(k,1)} e^{-\alpha_n z} + \frac{V_{22}(n,1)}{V_{22}(k,1)} e^{\alpha_n z}\right] d\alpha\right\} \quad . \tag{20}$$

We shall now normalize all dimensions by the mean radius of the coil and separate the terms.

$$\frac{V_d}{I} = \text{Vol } \alpha_{22}(\omega\mu\sigma_n R_5^2) \frac{3}{8} \omega\mu_0 R_5 \left\{\frac{N_3}{(R_2-R_1)L_3} \int_0^\infty \frac{e^{-\alpha(L_2+L_6)}}{\alpha^3} J(R_2,R_1)\left(1 - e^{-\alpha L_3}\right) \times \left[J_1(\alpha r)\left(\frac{V_{12}(n,1)}{V_{22}(k,1)} e^{-\alpha_n z} + \frac{V_{22}(n,1)}{V_{22}(k,1)} e^{\alpha_n z}\right)\right] d\alpha\right\} \tag{21}$$

(continued on next page)

$$\times \left\{ \frac{N_4}{(R_4-R_3)L_3} \int_0^\infty \frac{e^{-\alpha(L_2+L_6+L_5)}}{\alpha^3} \left(1 - e^{-\alpha(L_3-L_4-2L_5)}\right) J(R_4,R_3) \left(1 - e^{-\alpha L_4}\right) \right.$$

$$\left. \times \left[J_1(\alpha r) \left\{ \frac{V_{12}(n,1)}{V_{22}(k,1)} e^{-\alpha_n z} + \frac{V_{22}(n,1)}{V_{22}(k,1)} e^{\alpha_n z} \right\} \right] d\alpha \right\} = j\omega M' \quad .$$

Equation (21) represents the change in the mutual coupling due to the presence of the discontinuity. If we wish to calculate the change in impedance of the driver coil, Z_D', due to the flaw, we simply square the term in the first set of curly brackets and omit the term in the second set of curly brackets. Likewise, the change in impedance of the pickup coil is the square of the term in the second set of curly brackets with the first set omitted. Also the term in the square brackets is identical in both sets of curly brackets and needs to be calculated for only one.

We shall now discuss the calculation of the terms $V_{12}(n,1)$ and $V_{22}(n,1)$. In our actual computer programs we will be concerned only with the quotient of these terms, and we shall use a simple iterative method described in ref. 7. We shall redefine the terms as

$$\frac{V_{\ell 2}(n,1)}{V_{22}(k,1)} = 2^{k-n} e^{-(-1)^{\ell}\alpha_n z_{n-1}} \frac{V_{\ell 2}'(n,1)}{V_{22}'(k,1)} \left(\beta_{n+1}\ \beta_{n+2}\ .\ .\ .\ \beta_k\right) \quad . \qquad (22)$$

The letter n represents any arbitrary region under the coil and the letter k that of the region directly under the coil.

For the special case of n equal to one, we have

$$V_{\ell 2}(1,1) = V_{\ell 2}'(1,1) = \begin{cases} 0 \text{ if } \ell = 1 \\ 1 \text{ if } \ell = 2 \quad . \end{cases}$$

Therefore,

$$\frac{V_{22}(1,1)}{V_{22}(k,1)} = \frac{2^{k-1} e^{-\alpha_1 z_1}}{V_{22}'(k,1)} \left(\beta_2\ \beta_3\ .\ .\ .\ \beta_k\right) \quad . \qquad (23)$$

(1) We calculate the numerical value of the first transformation matrix as

$$V'_{i2}(2,1) \equiv \left[\beta_2 + (-1)^i \beta_1\right] = t_{i2}(2,1) \text{ for } i = 1,2 \quad , \qquad (24)$$

where

$$\beta_n = \frac{1}{\mu_n} \sqrt{\alpha^2 + j\omega\mu_0\mu_n\sigma_n R_5{}^2} = \frac{\alpha_n}{\mu_n}$$

and is dimensionless. The μ_n is the relative permeability of the layer with index n. (2) Then we determine the numerical value for the four elements of the transformation to the next layer. They are

$$t_{ij}(n,n-1) = \left[\beta_n + (-1)^{i+j}\beta_{n-1}\right] \exp\left[(-1)^j \alpha_{n-1}\left(z_{n-1} - z_{n-2}\right)\right] \quad . \qquad (25)$$

(3) From this we shall numerically calculate:

$$V'_{12}(n,1) = t_{11}(n,n-1)V'_{12}(n-1,1) + t_{12}(n,n-1)V'_{22}(n-1,1) \quad . \qquad (26)$$

$$V'_{22}(n,1) = t_{21}(n,n-1)V'_{12}(n-1,1) + t_{22}(n,n-1)V'_{22}(n-1,1) \quad . \qquad (27)$$

Step 1 is performed for the first region. Steps 2 and 3 are repeated for n = 3, 4 . . ., k.

The gamma factor, γ, used for all cases except defect calculations, is

$$\gamma = \frac{V_{12}(k,1)}{V_{22}(k,1)} = \frac{V'_{12}(k,1)}{V'_{22}(k,1)} \quad . \qquad (28)$$

For the case of defects the term in the square brackets in Eq. (21) becomes

$$\left[J_1(\alpha r) 2^{k-n} \left(V_{12}'(n,1) e^{-\alpha n (z - z_{n-1})} + V_{22}'(n,1) e^{+\alpha n (z - z_{n-1})} \right) \frac{\beta_{n+1}\ \beta_{n+2} \cdots \beta_k}{V_{22}'(k,1)} \right] , \qquad (29)$$

and for the special case of defects in region 1 it becomes

$$\left[J_1(\alpha r) 2^{k-1} \left(e^{-\alpha_1 (z_1 - z)} \right) \frac{\beta_2\ \beta_3 \cdots \beta_k}{V_{22}'(k,1)} \right] . \qquad (30)$$

We shall now consider a few examples. The γ factor for a single, semi-infinite conductor is:

$$\frac{V_{12}'(2,1)}{V_{22}'(2,1)} = \frac{\beta_2 - \beta_1}{\beta_2 + \beta_1} = \frac{\alpha - \beta_1}{\alpha + \beta_1} . \qquad (31)$$

The term in square brackets in Eq. (20) for a defect in region 1 is:

$$\frac{2\alpha e^{\alpha_1 z} e^{-\alpha_1 z_1}}{(\alpha + \beta_1)} . \qquad (32)$$

If we have two conductors, the γ factor becomes:

$$\frac{V_{12}'(3,1)}{V_{22}'(3,1)} = \frac{t_{11}(3,2) V_{12}'(2,1) + t_{12}(3,2) V_{22}'(2,1)}{t_{21}(3,2) V_{12}'(2,1) + t_{22}(3,2) V_{22}'(2,1)}$$

$$= \frac{(\beta_3 + \beta_2)(\beta_2 - \beta_1) e^{-\alpha_2 (z_2 - z_1)} + (\beta_3 - \beta_2)(\beta_2 + \beta_1) e^{+\alpha_2 (z_2 - z_1)}}{(\beta_3 - \beta_2)(\beta_2 - \beta_1) e^{-\alpha_2 (z_2 - z_1)} + (\beta_3 + \beta_2)(\beta_2 + \beta_1) e^{+\alpha_2 (z_2 - z_1)}} . \qquad (33)$$

The term in square brackets in Eq. (20) for a defect in region 2 is

$$\left[\frac{2\alpha (\beta_2 - \beta_1) e^{\alpha_2 z_1 - \alpha_2 z} + 2\alpha (\beta_2 + \beta_1) e^{-\alpha_2 z_1 + \alpha_2 z}}{(\beta_3 - \beta_2)(\beta_2 - \beta_1) e^{-\alpha_2 (z_2 - z_1)} + (\beta_3 + \beta_2)(\beta_2 + \beta_1) e^{+\alpha_2 (z_2 - z_1)}} \right] . \qquad (34)$$

The term in square brackets in Eq. (20) for a defect in region 1 is

$$\left[\frac{4\beta_2\beta_3 e^{\alpha_1 z - \alpha_1 z_1}}{(\beta_3 - \beta_2)(\beta_2 - \beta_1)e^{-\alpha_2(z_2 - z_1)} + (\beta_3 + \beta_2)(\beta_2 + \beta_1)e^{\alpha_2(z_2 - z_1)}}\right] . \quad (35)$$

Thus, in principle, we can analyze the response of a reflection coil above any number of layers.

CONSIDERATIONS FOR TEST DESIGN

We shall now consider some practical aspects in the design of eddy-current tests using reflection type coils.

The design of the eddy-current test is not automatic. The user must take the conductor parameters given in the problem, choose the coil and operating parameters, and run these in the computer program. The computer program will calculate the output of the coil and circuit which shows how well the measurements can be made using the selected parameters. Other parameters must be selected and run to determine which choice is optimum. The choice of the parameters used in the examples in each section is near optimum. Other reports referenced in the individual sections may be used to ensure that the initial trial is near optimum. Reference 9 gives a good overall description of the lift-off interactions in design.

We shall attempt to present an outline to follow in optimizing these tests, although due to the complex interactions between the many test variables it will become apparent that the outline cannot be followed exactly in every situation. Because of the interactions among the various parameters, this entire section on considerations for test design should be read before starting a design.

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[9] C. V. Dodd and W. A. Simpson, Jr., *Thickness Measurements Using Eddy-Current Techniques*, ORNL-TM-3712 (March 1972).

Maximize Sensitivity

The sensitivity to the desired test variable should be maximized. This is usually done with very large impedances of the driving and pickup circuits. Under these conditions, only the mutual coupling between the driver and pickup coils is affecting the tests. The sensitivity curves usually have very broad peaks so that it is not really necessary to operate at conditions necessary for the absolute maximum sensitivity.

Minimize the Undesired Effects

The sensitivity to variations in variables that we do not wish to measure should be minimized while keeping the sensitivity to the variables of interest as high as possible. We shall discuss these undesired variables in their general order of consideration in coil design problems.

Lift-Off Variations

Lift-off, or variations in the distance between the coil and conductor, is the largest source of error in most eddy-current tests. However, in many tests using phase sensing, the lift-off error can be reduced to insignificant proportions. The controllable factors influencing the phase variation due to lift-off are as follows.

Coil Geometry. — The shorter the driver coil, the smaller is the value of $\bar{r}^2\omega\mu\sigma$ at which the minimum lift-off effect occurs. In general, in order to make the value of $\bar{r}^2\omega\mu\sigma$ for minimum lift-off effect be the same as that for maximum sensitivity, the normalized length of the driver coil must be from 0.4 to 0.6. Most other effects tend to increase the value of $\bar{r}^2\omega\mu\sigma$ for minimum lift-off, and usually there is a problem getting this value low enough (or the coils short enough).

By "zero lift-off" we really mean the minimum value of lift-off, which is not actually zero, but some finite value of lift-off because of the thickness of the insulation and the bearing surface on the face of the probe. The "zero lift-off" is a normalized thickness, and should not be confused with the minimum lift-off effect, which is a phase shift due to a lift-off variation. The larger the "zero lift-off," the larger is the value of $\bar{r}^2\omega\mu\sigma$ at which the minimum lift-off effect occurs. Therefore, we try to make the "zero lift-off" as small as practical. For a coil with Teflon tape over the face, the normalized "zero lift-off" ranges from about 0.3 for a mean radius of 0.020 in. to about 0.025 for a mean radius of 0.40 in. For the same coils without the Teflon tape over the face, the normalized "zero lift-off" would range from about 0.1 to 0.015, respectively.

The normalized values of the inner and outer radii of the driver coil and pickup coils have only a small effect on the value of $\bar{r}^2\omega\mu\sigma$ at which the minimum lift-off effect occurs. The values of R1, R2, R3, and R4 used in this report (0.75, 1.25, 0.35, and 0.7, respectively) represent a compromise between those producing a minimum value of $\bar{r}^2\omega\mu\sigma$ for the minimum lift-off effect and those producing maximum voltage from a reflection-type coil system.

Lift-Off Range. — This is the range of variation of the lift-off, or coil to conductor spacing and usually represents a compromise between what is easily obtainable and the amount of error introduced. If the lift-off is increased from "zero lift-off" (the minimum) to a maximum value, this produces a phase shift known as the lift-off effect. The smaller the lift-off range, the smaller is the lift-off effect and the value of $\bar{r}^2\omega\mu\sigma$ at which the minimum lift-off effect occurs.

Range of Measurements. — The range of measurements is the range of the variable such as thickness, cladding thickness, or conductivity that we desire to measure. The smaller the range of measurements, the smaller is the lift-off effect. In most cases the value of $\bar{r}^2\omega\mu\sigma$ for minimum lift-off effect tends to increase slightly as the range increases.

Attenuator Parameters and Number of Turns. — The attenuator parameters, unlike the previous parameters, do not require any additional numerical integrations and, therefore, require very little additional computation time. Since these parameters will tend to increase the value of $\bar{r}^2\omega\mu\sigma$ for minimum lift-off effect, the coil must be made shorter than the optimum indicated in the previous paragraphs. The attenuator parameters consist of the resistance and capacitance in the instrument driving and pickup circuits. The attenuator parameters, together with the turns on the coil, play an important part in the total instrument response. Selection of the values of these parameters should proceed with the following steps.

1. Determine the desired ratio of ω to ω_0 (the resonant frequency). The coil inductance and the shunt capacitance (including cable, coil interwinding, and amplifier input capacitance) in both the driving and pickup circuits form a resonant circuit that limits the high frequency response of the probe and, therefore, the noise. With no capacitance in the circuit, the signal with the probe on a conductor will increase continuously with frequency, at a rate somewhat greater than ω to the first power. The ratio of the resonant frequency to the operating frequency is given by

$$\frac{\omega_0}{\omega} = \frac{1}{\omega\sqrt{C\ L\ Im}} \quad , \tag{36}$$

where C is the shunt capacitance, L is the coil inductance, and Im represents the normalized imaginary part of the coil impedance. Both the ratio ω_0/ω and Im are calculated in the programs. The normal value of the ratio ranges from 2 to 20, with 10 being the most used. For a ratio greater than 20, the noise becomes troublesome. With smaller ratios, the coils cannot be made short enough to achieve good lift-off compensation, and component variation causes larger phase shifts.

2. Determine approximate coil inductance. The minimum coil inductance, determined by the system's low frequency operation and the minimum output resistance, R_0, can be approximated by:

$$\text{Min Inductance} \approx \frac{RO_{min}}{1.5\ Im\left[\omega_{min}\left(\frac{\omega_0}{\omega_{min}}\right)\right]} \quad . \tag{37}$$

Substituting approximate values for the minimum driving resistance and the normalized imaginary part of the impedance gives

$$\text{Min Inductance} \approx \frac{42}{\left[\omega_{min}\left(\frac{\omega_0}{\omega_{min}}\right)\right]}, \qquad \text{(henries)} \tag{38}$$

where ω is the minimum operating frequency under consideration and ω_0/ω_{min} is the ratio of the resonance frequency to the minimium frequency.

The maximum inductance will be limited by the high frequency response of the system and is approximated by:

$$\text{Max Inductance} \approx \frac{1}{C\ \text{Im}\left[\omega_{max}\ \frac{\omega_0}{\omega_{max}}\right]^2}, \tag{39}$$

The minimum capacitance in the leads, coils, and amplifiers will usually be approximately 100 pF. Thus, we have

$$\text{Max Inductance} \approx \frac{1}{8 \times 10^{-11}\left[\omega_{max}\ \frac{\omega_0}{\omega_{max}}\right]^2}. \tag{40}$$

The probe may be designed to operate over a very wide frequency range or for a single frequency, where $\omega_{min} = \omega_{max}$. A wire gage must be chosen (using the coil design option) to give an inductance somewhere between the maximum and minimum values. For coils with the greatest range of operating frequency, the inductance of the driver and pickup coils should be approximately the same, since the lead capacitances will usually be similar.

3. Once the exact inductance has been determined, the capacitance necessary to give the desired ratio of ω_0/ω must be selected (for each value of operating frequency). This is given by

$$C = \frac{1}{L\ \text{Im}\left[\omega\left(\frac{\omega_0}{\omega}\right)\right]^2}, \tag{41}$$

and the ratio ω_0/ω is calculated by the attenuator design option in the programs.

4. Next, the value of driver series or pickup shunt resistance needed to give a minimum temperature drift (due to variations in the coil dc resistance) must be determined. A rough approximation for this resistance is

$$R0 \approx 1.25\ \omega L_D \left(\frac{\omega_0}{\omega}\right) \tag{42}$$

for the driver series resistance (R0), and

$$R9 \approx 1.75\ \omega L_{PU} \left(\frac{\omega_0}{\omega}\right) \tag{43}$$

for the pickup shunt resistance (R9). It should be emphasized here that these values may be in error by a factor of 2. The only way to get an accurate value of the resistance for minimum drift will be to vary R0 and R9 and calculate the drift. Positive values of the drift indicate that the resistance should be increased, negative values of the drift indicate the resistance should be decreased. The drifts will not become exactly zero, and there is an interaction between R0 and R9 so that several calculations on each may be necessary. Drifts on the order of $0.005°/°C$ are practical, both analytically and experimentally.

5. Once the proper attenuator has been obtained, it is necessary to reexamine the lift-off error since this is affected by the attenuator parameters. It may be necessary to vary the coil length, the zero lift-off, and the lift-off range in order to minimize the lift-off error. This unfortunately requires that the coil and attenuator be redesigned. Therefore, since it is known that the addition of the attenuator will increase the value of $\bar{r}^2\omega\mu\sigma$ at which the minimum lift-off error occurs, it is desirable to design the coil without an attenuator so that the value of $\bar{r}^2\omega\mu\sigma$ for minimum lift-off error is less than that for maximum sensitivity. In Fig. 5 we show how the fractional increase in the value of $\bar{r}^2\omega\mu\sigma$ for minimum lift-off error increases as the ratio ω_0/ω decreases for a particular coil. The value of $\bar{r}^2\omega\mu\sigma$

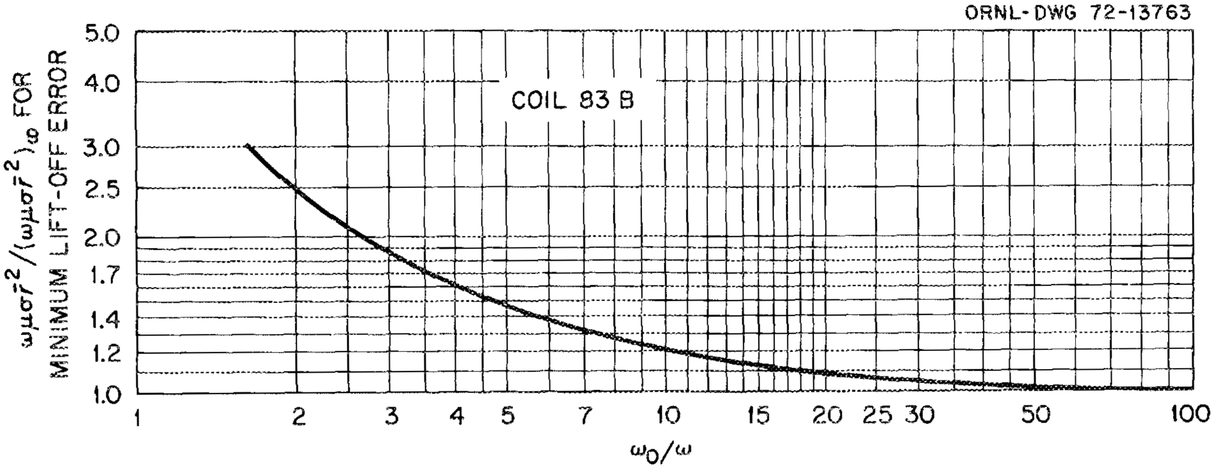

Fig. 5. Ratio of the Value of $\bar{r}^2\omega\mu\sigma$ for Minimum Lift-Off Error for an Attenuator Having a Resonant to Operating Frequency of ω_0/ω to the value of $\bar{r}^2\omega\mu\sigma_\infty$ for Minimum Lift-Off Error with an Infinite Ratio of ω_0/ω, Plotted Against ω_0/ω.

for minimum lift-off error with an infinite ratio of ω_0/ω has been taken as unity. This should give at least an estimate of how much the value of $\bar{r}^2\omega\mu\sigma$ will be increased and should be taken into account in the original selection of the coil parameters.

The series of steps outlined in this section should serve as a rough guide to good coil design.

REFLECTION COIL ABOVE A SINGLE CONDUCTING PLANE

We shall now consider the case of a reflection coil above a single conductor. This computer program calculates the magnitude and phase of the voltage that is fed to the phase measuring circuits of the phase-sensitive eddy-current instruments and is designed to help analyze eddy-current measurements of conductivity.

The program calculates the magnitude and phase of the induced voltage at 5 different values of lift-off for each of 3 different conductivity values, making a total of 15 calculations. This allows one to examine the sensitivity to lift-off variations as well as conductivity variations. In addition, the program also calculates the phase shift with the discriminator adjusted to give the same phase on the nominal conductivity sample with maximum and minimum lift-off. The phase on the nominal conductivity sample with minimum lift-off is taken as zero, and all other phase shifts are measured relative to it.

The equations that are evaluated are Eq. (8) for the mutual coupling, Eq. (9) for the driver coil impedance, and Eq. (17) for the pickup coil impedance. The gamma factor for the single, semi-infinite conductor is given in Eq. (31).

The programs are written in both BASIC and FORTRAN for use on the PDP-10. The BASIC program follows.

To use this program, one must first divide all dimensions by the mean radius of the driver coil. Then the following lines must be typed into the program.

```
250     R5 = (numerical value of driver coil mean radius in inches)
260     R1 = (numerical value of normalized driver coil inner radius)
270     R2 = (numerical value of normalized driver coil outer radius)
280     L3 = (numerical value of normalized driver coil length)
290     R3 = (numerical value of normalized pickup coil inner radius)
300     R4 = (numerical value of normalized pickup coil outer radius)
310     L4 = (numerical value of normalized pickup coil length)
320     L5 = (numerical value of normalized pickup coil recess from
             face of driver)
330     L6 = (numerical value of normalized driver coil minimum lift-off)
340     R6 = (numerical value of resistance of driver coil in ohms)
350     R7 = (numerical value of total resistance of both pickup coils
             in ohms)
360     N3 = (number of turns on driver coil)
370     N4 = (number of turns on each pickup coil)
380     R0 = (output series resistance of driving amplifier in ohms)
390     R9 = (input shunt resistance of pickup amplifier in ohms)
400     C6 = (total shunt capacitance in driving circuit in farads)
410     C7 = (total shunt capacitance in pickup circuit in farads)
420     V0 = (output voltage of driving amplifier in volts)
430     G5 = (gain of pickup amplifier)
440     F  = (operating frequency in Hertz)
```

450 L2 = (numerical value of normalized driver coil lift-off increment)

510 K1 = (numerical value of resistivity of conductor in microhm centimeter)

515 U1 = (numerical value of relative permeability of conductor)

750 M0 = (numerical value of fractional conductivity change)

The program may now be run. The print-out by the computer will have the following format.

```
R1= (R1)      R2= (R2)        DRIVER LENGTH IS (L3)
R3= (R3)      R4= (R4)        PICK UP LENGTH IS (L4)
COIL MEAN RADIUS (R5) INCHES       OPERATING FREQUENCY (F)
PICK UP RECESSED (L5)
MINIMUM LIFT-OFF (L6) LIFT-OFF INCREMENT (L2)
U1= (U1)      M1= .......     RESISTIVITY= (K1)     MICROHM CM
TOTAL CONDUCTIVITY VARIATION ABS (200.M0)%
DRIVER RES    INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT
  (R6)          ......          (N3)          (C6)           .....
PICKUP RES    INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT
  (R7)          ......          (N4)          (C7)           .....
DRIVING VOLT  SERIES RES      AMP GAIN      INPUT IMP
  (V0)          (R0)            (G5)          (R9)
DISCRIMINATOR VOLTAGE IS .....

  (L6)          (L6+L2)         (L6+2L2)      (L6+3L2)       (L6+4L2)

  .....         .....           .....         .....          .....
  .....         .....           .....         .....          .....
  .....         .....           .....         .....          .....

  .....         .....           .....         .....          .....
  .....         .....           .....         .....          .....
    0           .....           .....         .....          .....

  .....         .....           .....         .....          .....
  .....         .....           .....         .....          .....
  .....         .....           .....         .....          .....
 PHASE SHIFT ..... LIFT-OFF .....             %.....
 DEGREE .....               .....
 1 COIL DESIGN    2 ATTEN. DESIGN   3 DRIFT CHECK   4 CON CAL
  ?
```

The various symbols enclosed in parentheses are used to indicate that the numerical value of the symbol will be printed.

There are five columns of data, one under each value of lift-off. Each column is divided into three sections of three lines each. These sections correspond, from top to bottom, to the three values (−100*MO, 0, and +100*MO %) of variations from the nominal conductivity. The three lines in each section are, from top to bottom, the magnitude of the voltage out of the pickup amplifier, the phase shift between the voltage out of the pickup amplifier and the driving voltage, and the phase shift between the voltage out of the pickup amplifier with the discriminator set to give the same phase shift with minimum lift-off and maximum lift-off on the nominal conductivity sample. The phase shift in the third line is always measured from the nominal conductivity sample with minimum lift-off. The voltage out of the pickup amplifier will be in volts and be either peak-to-peak or RMS, whichever is used for VO, the output voltage of the driving amplifier. The value of the dimensionless product $R_5^2\omega\mu_1\sigma_1$ is also calculated and printed out as $M1 = (R_5^2\omega\mu_1\sigma_1)$. The inductance in henries of the driving coil in air and the normalized imaginary part of the driving coil impedance, with nominal conductivity and nominal lift-off (L6+2L2), is also printed. Likewise the inductance in henries of both pickup coils in air and the normalized imaginary part of the pickup coils' impedance with nominal conductivity and lift-off is also printed. The total phase shift for the 200*MO % conductivity variation, the maximum phase shift due to lift-off, and the maximum percent of range error in conductivity measurements due to lift-off are given. The phase shifts are given first in radians and then in degrees.

The program then enters a branching loop that allows the following options, depending on which of 1, 2, 3, or 4 is typed as input after the question mark.

1. Coil Design

If a 1 is typed by the operator after the question mark, the program will enter the Coil Design Loop. This loop will allow the number of turns on the driver and pickup coils to be varied. The loop will allow the wire gage to be given and then calculate the number of turns and coil resistance, or it will allow the number of turns to be entered and calculate the gage and coil resistance, or both turns and gage can be entered. If zeros are entered for both the gage and turns of either the driver or pickup coils, the present value of these will be retained. The program then starts with the label

DRIVER RES INDUCTANCE NO TURNS SHUNT CAP NOR IM PT ,

and the remainder of the program is recalculated and printed, with the "new" coil in the circuit. However, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

2. Attenuator Design

This loop will allow the driver series resistance, R0, the driver shunt capacitance, C6, the amplifier input impedance, R9, and the shunt capacitance in the pickup circuit, C7, to be varied. If a 2 is typed after the question mark, the computer will respond with

DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP .

The resistance is to be given in ohms, and the capacitance in farads. If zero is typed in for any value, the present value in the computer will be retained. After the input data and a carriage return are typed, the computer will calculate the ratio of resonant frequency to operating frequency for the particular L-C circuit, a very rough value of resistance for minimum temperature drift, and the ratio between the resistance and reactance in the circuit for both the driver and pickup circuits. The program then starts with the label

DRIVER RES INDUCTANCE NO TURNS SHUNT CAP NOR IM PT ,

and the remainder of the program is recalculated and printed with the "new" attenuator in the circuit. Again, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

3. Drift Check

This loop calculates the effect of the drift of any of the circuit or sample parameters after the instrument has been calibrated and adjusted. If a 3 is typed as input, the program will respond with the percent variation, the parameter varied, the maximum change in phase (both radians and degrees) of any of the 15 different phases calculated (5 lift-off values for each of 3 different conductivity values) and the percent of the range the drift represents. The percent variation of each parameter may be varied independently. The following table gives the parameter, the line number, and the constant to be varied:

Parameter	Line Number	Constant
Driver Resistance	8610	E1
Pickup Resistance	8620	E2
Driver Shunt Cap.	8630	E3
Pickup Shunt Cap.	8640	E4
Series Resistance	8650	E7
Amplifier Input Resistance	8660	E8
Applied Voltage	8670	E9
Frequency	8680	A1
Mean Radius	8690	A2
Resistivity	8700	A8

For example, to put in a 2% variation in the driver coil resistance, one would type:

8610 E1 = .02

The amount that each parameter is varied must be set before the program is run. All of the variations are 0.01 or 1% in the current version of the program. Since the phase shift produced by the parameter variation is quite linear over a range of about 10%, a linear interpolation or extrapolation may be used from the 1% parameter variation. If zero is typed in for any parameter variation, that parameter will not be varied nor will it be typed out in the list of parameter variations. When the calculation is completed and the drifts printed, the program returns to the branch point and repeats the question

1 Coil Design 2 Atten. Design 3 Drift Check 4 Con Cal .

The first seven drifts do not require that the numerical integrations to calculate M, Z_{DR}, and Z_{PU} be repeated, but they must be repeated to calculate the drifts due to frequency, mean radius, and resistivity changes. Therefore, the calculation of these last three drifts requires a considerable amount of computer time.

4. Con Cal

This loop is to continue calculations. If a series of calculations is to be made, a loop may be established at this point. However, in the present version of the program, if a 4 is typed as input, the program will end.

Sample Calculation of RFCON

Let us suppose we wish to design a reflection-type coil to measure electrical conductivity of a thick metal plate. The coil values below were chosen by trial and error to give good results. The driver coil has a mean radius of 0.300 in., inner and outer radii of 0.225 in. and 0.375 in., and a length of 0.180 in. The pickup coils have inner and outer radii of 0.105 and 0.210 in., a length of 0.060 in., and are mounted flush with the ends of the driver coil. The driver coil has 810 turns of No. 36 wire with a resistance of 57.555 Ω, and the pickup coils have 2925 turns each of No. 48 wire, with a resistance of 3443.01 Ω for both coils. The input resistances of both the driver series and the pickup amplifier are chosen to be 1 MΩ. The shunt capacitances in both circuits are chosed to be 1 pF. This corresponds to practically infinite source and detector impedances, so that only the mutual coupling, M, affects the phases. The minimum lift-off is taken to be 0.030 in. with a lift-off increment of 0.0075 in. The nominal resistivity of the material is 2.95 μΩ cm, the variation in conductivity is ±5%, and the relative magnetic permeability is 1. The frequency is 500 Hz; the output voltage of the driving amplifier is 10 V, and the gain of the pickup amplifier is unity (a unity gain allows the actual gain needed in the amplifier to be calculated by dividing the maximum output voltage with unity gain into 10).

The program RFCON is assumed to be in the active core, and the following information is typed into the computer. All linear dimensions are normalized by dividing by the coil mean radius, except for the coil mean radius, which is in inches.

```
250     R5 = .300
260     R1 = .75
270     R2 = 1.25
280     L3 = .6
290     R3 = .35
300     R4 = .70
310     L4 = .2
320     L5 = 0
330     L6 = .1
340     R6 = 57.555
350     R7 = 3443.01
360     N3 = 810
370     N4 = 2925
380     R0 = 1E6
390     R9 = 1E6
400     C6 = 1E-12
410     C7 = 1E-12
420     V0 = 10
430     G5 = 1
440     F  = 500
450     L2 = .025
510     K1 = 2.95
515     U1 = 1
750     M0 = -0.05
```

The program may now be run with the following results. The data inputed from the terminal by the user are underlined. A carriage return must be typed by the user at the end of each input line.

```
RFCØN(BASIC)


R1= 0.75         R2= 1.25         DRIVER LENGTH IS 0.6
R3= 0.35         R4= 0.7          PICK UP LENGTH IS 0.2
CØIL MEAN RADIUS 0.3 INCHES       ØPERATING FREQUENCY 500
PICK UP RECESSED 0
MIN LIFT-ØFF= 0.1 LIFT-ØFF INCREMENT= 0.025
U1= 1            M1= 7.77051     RESISTIVITY= 2.95 MICRØHM CM
TØTAL CØNDUCTIVITY VARIATIØN 10 %
DRIVER RES       INDUCTANCE       NØ TURNS         SHUNT CAP       NØR IM PT
 57.555           9.60145E-3       810              1.00000E-12     0.879034
PICKUP RES       INDUCTANCE       NØ TURNS         SHUNT CAP       NØR IM PT
 3443.01          8.83174E-2       2925             1.00000E-12     0.991484
DRIVING VØLT     SERIES RES       AMP GAIN         INPUT IMP
 10               1000000          1                1000000
DISCRIMINATØR VØLTAGE IS-2.34257E-6

 0.1              0.125            0.15             0.175           0.2

 3.46578E-5       3.18994E-5       2.93786E-5       2.70755E-5      2.49714E-5
-0.784464        -0.790631        -0.797096        -0.803805       -0.810714
 1.53083E-2       1.50008E-2       1.48557E-2       1.49523E-2      1.53638E-2

 3.55548E-5       3.27167E-5       3.01235E-5       2.77546E-5      2.55908E-5
-0.798064        -0.804088        -0.81042         -0.817005       -0.823797
 0               -2.95155E-4      -4.46215E-4      -3.72447E-4      7.45058E-9

 3.64118E-5       3.34975E-5       3.08349E-5       2.84030E-5      2.61821E-5
-0.811008        -0.816891        -0.823092        -0.829554       -0.83623
-1.44989E-2      -1.47715E-2      -1.49175E-2      -1.48548E-2     -1.45084E-2
PHASE SHIFT 2.98064E-2 LIFT-ØFF 5.08092E-4 % 1.70464
DEGREE 1.70778                    2.91116E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?1

DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS
 ?36,0,48,0
DRIVER 924 TURNS ØF # 36 WIRE 33 /LAYER 28 LAYERS 60.2723 ØHM
PICKUP 3225 TURNS EA # 48 WIRE 43 /LAYER 75 LAYERS 3569.24 ØHMS TØTAL
DRIVER RES       INDUCTANCE       NØ TURNS         SHUNT CAP       NØR IM PT
 60.2723          1.24943E-2       924              1.00000E-12     0.879034
PICKUP RES       INDUCTANCE       NØ TURNS         SHUNT CAP       NØR IM PT
 3569.24          0.107363         3225             1.00000E-12     0.991484
DRIVING VØLT     SERIES RES       AMP GAIN         INPUT IMP
 10               1000000          1                1000000
```

```
DISCRIMINATØR VØLTAGE IS-2.94602E-6

 0.1            0.125          0.15           0.175          0.2

 4.35848E-5     4.01159E-5     3.69458E-5     3.40495E-5     3.14035E-5
-0.784532      -0.790699      -0.797163      -0.803873      -0.810782
 1.53083E-2     1.50007E-2     1.48557E-2     1.49523E-2     1.53638E-2

 4.47128E-5     4.11437E-5     3.78826E-5     3.49035E-5     3.21824E-5
-0.798131      -0.804155      -0.810487      -0.817073      -0.823865
 0             -2.95207E-4    -4.46253E-4    -3.72484E-4     0

 4.57906E-5     4.21256E-5     3.87772E-5     3.57190E-5     3.29260E-5
-0.811076      -0.816958      -0.823159      -0.829622      -0.836298
-1.44989E-2    -1.47715E-2    -1.49175E-2    -1.48549E-2    -1.45084E-2
PHASE SHIFT 2.98064E-2 LIFT-ØFF 5.08152E-4 % 1.70484
DEGREE 1.70778                 2.91150E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?2

DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP
 ?4.1E2,1.2E-7,5.4E3,1.1E-8
DVR CT 8.76802 BELØW RES 302.529 ØPT RES 11.8828 RES/REACTANCE
P-U CT 9.30217 BELØW RES 3110.81 ØPT RES 16.1475 RES/REACTANCE
DRIVER RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 60.2723        1.24943E-2     924            1.20000E-7     0.879034
PICKUP RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 3569.24        0.107363       3225           1.10000E-8     0.991484
DRIVING VØLT   SERIES RES     AMP GAIN       INPUT IMP
 10             410            1              5400
DISCRIMINATØR VØLTAGE IS-4.16057E-3

 0.1            0.125          0.15           0.175          0.2

 5.59413E-2     5.15255E-2     4.74844E-2     4.37876E-2     4.04064E-2
-0.989504      -0.996298      -1.00335       -1.0106        -1.01802
 1.51480E-2     1.47468E-2     1.45944E-2     1.47688E-2     1.53430E-2

 5.73849E-2     5.28423E-2     4.86857E-2     4.48838E-2     4.14070E-2
-1.00278       -1.00945       -1.01639       -1.02354       -1.03086
 0             -4.25383E-4    -6.19113E-4    -5.01692E-4     0

 5.87644E-2     5.41004E-2     4.98331E-2     4.59306E-2     4.23623E-2
-1.01541       -1.02197       -1.02879       -1.03584       -1.04306
-1.43376E-2    -1.47751E-2    -1.49971E-2    -1.49231E-2    -1.44788E-2
PHASE SHIFT 2.96226E-2 LIFT-ØFF 7.48619E-4 % 2.52719
DEGREE 1.69725                 4.28928E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?3
```

```
SYSTEM DRIFT VARIATIØNS
% VARIATN      PARAMETER       RADIAN          DEGREE          % ØF RANGE
 1             DRIVER RES       5.94109E-5      0.003404        0.20056
 1             PICKUP RES       1.25870E-4      7.21183E-3      0.424913
 1             DVR SHUNT CAP  -2.27377E-4     -1.30277E-2     -0.76758
 1             P-U SHUNT CAP  -7.46027E-4     -4.27442E-2     -2.51844
 1             SERIES RES       1.50037E-3      8.59648E-2      5.06495
 1             AMP INPUT RES  -4.83483E-4     -2.77016E-2     -1.63215
 1             APPLIED VØLT   -1.02489E-3     -5.87217E-2     -3.45982
 1             FREQUENCY      -6.11736E-3     -0.350499       -20.651
 1             MEAN RADIUS    -8.12030E-3     -0.465259       -27.4126
 1             RESISTIVITY     2.99047E-3      0.171341        10.0952
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?4
```

The user has exercised all the design options available, and these options may be repeated, omitted, or taken in any order. The BASIC version of the program RFCON follows.

```
1  REM RFCØN(BASIC)
10 REM REFLECTIØN CØIL ØN A SINGLE CØNDUCTØR
40 DIM A(3,5),B(3,5),C(3,5),D(3,5),E(3,5),F(3,5)
50 DIM M(3,5),P(3,5),Q(3,5)
199 REM CØNSTANT
200 P9=3.14159
210 P8=180/P9
249 REM CØIL DATA
250R5=.3
260R1=.75
270R2=1.25
280L3=.6
290R3=.35
300R4=.7
310L4=.2
320L5=0
330L6=.1
340R6=57.555
350R7=3443.01
360N3=810
370N4=2925
379 REM CIRCUIT DATA
380R0=1E6
390R9=1E6
400C6=1E-12
410C7=1E-12
420V0=10.0
430G5=1
440F=500
450L2=.025
470L7=L3-2*(L4+L5)
480L8=L7+L4
490L9=L5+2*L6
499 REM CØNDUCTØR DATA
500 DIM K(3),N(3),L(5)
510 K1=2.95
515 U1=1
520 GØ SUB 600
540 GØ TØ 750
599 REM SUBRØUTINE FØR M
600 W=2*P9*F
610 M1=.5094*U1*F*R5*R5/K1
620 RETURN
750 M0=-.05
770 U9=(U1-1)/(U1+1)
999 REM PRINT CØIL DATA
1000 PRINT "R1=";R1,"R2=";R2,"DRIVER LENGTH IS";L3
1010 PRINT"R3=";R3,"R4=";R4,"PICK UP LENGTH IS";L4
1020 PRINT "CØIL MEAN RADIUS";R5;"INCHES      ØPERATING FREQUENCY";F
1030 PRINT "PICK UP RECESSED";L5
1040 PRINT "MIN LIFT-ØFF=";L6;"LIFT-ØFF INCREMENT=";L2
1050 PRINT "U1=";U1,"M1=";M1,"RESISTIVITY=";K1;"MICRØHM CM"
1060 PRINT "TØTAL CØNDUCTIVITY VARIATIØN";200*ABS(M0);"%"
1100 REM PRØGRAM BEGINS
1110 REM FØR INTEGRATIØNS
1120 GØ SUB 1500
1130 REM FØR INDUCTANCES AND CIRCUIT; MAGNITUDE AND PHASE
```

```
1140 GØ SUB 6000
1150 REM FØR DISCRIMINATØR VØLTAGE AND PHASE SHIFT
1160 GØ SUB 6500
1170 REM FØR PRINTING ØF RESULTS
1180 GØ SUB 6700
1190 REM FØR AV. PHASE SHIFT AND LIFT-ØFF ERRØR
1200 GØ SUB 7000
1400 REM FØR CØIL AND ATTENUATØR DESIGNS, AND DRIFT
1410 GØ TØ 7200
1499 REM SUBRØUTINE FØR INTEGRATIØN
1500 A3=0
1510 A4=0
1520 FØR I=1 TØ 3
1530 FØR J=1 TØ 5
1540 A(I,J)=0
1550 B(I,J)=0
1560 C(I,J)=0
1570 D(I,J)=0
1580 E(I,J)=0
1590 F(I,J)=0
1600 NEXT J
1610 NEXT I
1620 LET S2=5
1630 B1=0
1640 B2=5
1650 S1=1E-2
1660 FØR X=B1+S1/2 TØ B2 STEP S1
1670 GØ SUB 2000
1680 NEXT X
1690 B1=B2
1700 B2=B2+S2
1710 S1=.05
1720 IF X<9 THEN 1660
1730 S1=.1
1740 IF X<29 THEN 1660
1750 S1=.2
1760 IF X<39 THEN 1660
1770 S1=.5
1780 IF X<79 THEN 1660
1790 RETURN
1998 REM SUBRØUTINE FØR L-FACTØR AND INTEGRANTS
1999 REM FØR J-FACTØR
2000 GØ SUB 2700
2010 W5=0
2020 W2=0
2030 W6=0
2040 W7=0
2050 W4=1
2060 W8=1
2070 W3=1
2080 IF X*L5>20 THEN 2100
2090 W5=EXP(-X*L5)
2100 IF X*L2>20 THEN 2120
2110 W2=EXP(-X*L2)
2120 IF X*L6>20 THEN 2140
2130 W6=EXP(-X*L6)
2140 IF X*L7>20 THEN 2160
```

```
2150 W7=EXP(-X*L7)
2160 IF X*L4>15 THEN 2220
2170 W4=1-EXP(-X*L4)
2180 IF X*L8>15 THEN 2220
2190 W8=1-EXP(-X*L8)
2200 IF X*L3>15 THEN 2220
2210 W3=1-EXP(-X*L3)
2220 IF X>30 THEN 2460
2230 IF X*L9>20 THEN 2460
2240 A5=W6*W6*W3*W4*W5*W8*S3
2250 A6=W6*W6*W3*W3*S4
2260 A7=W6*W6*W4*W4*W5*W5*W8*W8*S5
2270 L(1)=1
2280 FØR J=2 TØ 5
2290 L(J)=0
2300 IF J*X*L2>20 THEN 2320
2310 L(J)=W2*L(J-1)
2320 NEXT J
2329 REM FØR GAMMA FACTØR
2330 GØ SUB 3200
2340 FØR I=1 TØ 3
2350 FØR J=1 TØ 5
2360 Q1=K(I)*L(J)*L(J)
2370 Q2=-N(I)*L(J)*L(J)
2380 A(I,J)=A(I,J)+Q2*A5
2390 B(I,J)=B(I,J)+Q1*A5
2400 C(I,J)=C(I,J)+Q2*A6
2410 D(I,J)=D(I,J)+Q1*A6
2420 E(I,J)=E(I,J)+Q2*A7
2430 F(I,J)=F(I,J)+Q1*A7
2440 NEXT J
2450 NEXT I
2460 A3=A3+2*(X*L3-W3)*S4
2470 A4=A4+(4*(X*L4-W4)-2*W7*W4*W4)*S5
2480 RETURN
2699 REM SUBRØUTINE FØR J5=J(R1,R2)/X↑3,J6=J(R3,R4)/X↑3
2700 R=R1
2710 GØ SUB 2900
2720 J1=Q2
2730 R=R2
2740 GØ SUB 2900
2750 J5=Q2-J1
2760 R=R3
2770 GØ SUB 2900
2780 J3=Q2
2790 R=R4
2800 GØ SUB 2900
2810 J6=Q2-J3
2820 S3=S1*J5*J6
2830 S4=S1*J5*J5
2840 S5=S1*J6*J6
2850 RETURN
2899 REM SUBRØUTINE FØR Q2=J(R,0)*X↑3
2900 Z=X*R
2910 IF Z>5 THEN 3000
2920 Q1=R*R*R/2
2930 Q2=Q1/3
```

```
2940 Q3=INT(2*Z)+3
2950 FØR Q=1 TØ Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 GØ TØ 3050
3000 Q1=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
3010 Q1=((Q1-0.1730503)/Z+0.7034845)/Z-0.064109E-3
3020 Q2=(((-5.817517/Z+2.105874)/Z-0.6896196)/Z+0.4952024)/Z
3030 Q2=(Q2-0.187344E-2)/Z+0.7979095
3040 Q2=(1-SQR(Z)*(Q2*CØS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3198 REM SUBRØUTINE FØR GAMMA FACTØR(K(I),N(I))
3199 REM AND BETA(X1,Y1)
3200 Q1=X*X
3210 Q2=Q1*Q1
3220 FØR I=1 TØ 3
3230 M9=M1*(1-(I-2)*M0)
3240 K(I)=U9
3250 N(I)=0
3260 IF M9<Q1*1E-12 THEN 3350
3270 Q3=SQR(Q2+M9*M9)
3280 X1=.707106781*SQR(Q3+Q1)/U1
3290 Y1=.707106781*SQR(Q3-Q1)/U1
3300 Q4=X-X1
3310 Q5=X+X1
3320 Q6=Q5*Q5+Y1*Y1
3330 K(I)=(Q4*Q5-Y1*Y1)/Q6
3340 N(I)=-2*Y1*X/Q6
3350 NEXT I
3360 RETURN
5999 REM SUBRØUTINE FØR CIRCUIT, MAGNITUDE, AND PHASE
6000N1=N3/((R2-R1)*L3)
6010N2=N4/((R4-R3)*L4)
6020Q0=6.300475204E-7*F*R5
6030 W1=W*C6*R0
6040 W2=W*C7*R9
6050 W3=1-W1*W2
6060 W4=W1+W2
6070 FØR I=1 TØ 3
6080 FØR J=1 TØ 5
6090Z8=Q0*N1*N2*A(I,J)
6100Z9=Q0*N1*N2*B(I,J)
6110Z=Q0*N1*N1*C(I,J)
6120Z2=Q0*N1*N1*(D(I,J)+A3)
6130Z1=Q0*N2*N2*E(I,J)
6140Z3=Q0*N2*N2*(F(I,J)+A4)
6150 Q1=R0+R6+Z-W1*Z2
6160 Q2=R9+R7+Z1-W2*Z3
6170 Q3=Z2+W1*(R6+Z)
6180 Q4=Z3+W2*(R7+Z1)
6190 Q5=Z8*Z8-Z9*Z9
6200 Q6=2*Z8*Z9
6210 Q7=Q1*Q2-Q3*Q4-(W3*Q5-W4*Q6)
6220 Q8=Q1*Q4+Q3*Q2-(W4*Q5+W3*Q6)
6230 Q9=Z8*Q7+Z9*Q8
6240 W5=Z9*Q7-Z8*Q8
```

```
6250 M(I,J)=G5*R9*V0*SQR(Q9*Q9+W5*W5)/(Q7*Q7+Q8*Q8)
6260 P(I,J)=ATN(W5/Q9)
6270 IF Q9>0 THEN 6290
6280 P(I,J)=P(I,J)+SGN(W5)*P9
6290 NEXT J
6300 NEXT I
6310 RETURN
6499 REM SUBRØUTINE FØR DISC. VØLTAGE AN PHASE SHIFT
6500 Q1=M(2,5)*SIN(P(2,5))-M(2,1)*SIN(P(2,1))
6510 Q2=-M(2,5)*CØS(P(2,5))+M(2,1)*CØS(P(2,1))
6520 Q3=ATN(Q1/Q2)
6530 IF Q2>0 THEN 6550
6540 Q3=Q3+SGN(Q1)*P9
6550 V1=M(2,1)*SIN(Q3+P(2,1))
6555 Ø1=Q3
6556 Ø2=V1
6560 FØR I=1 TØ 3
6570 FØR J=1 TØ 5
6580 Q(I,J)=Q3-ATN(V1/SQR(M(I,J)*M(I,J)-V1*V1))+P(I,J)
6590 NEXT J
6600 NEXT I
6610 RETURN
6699 REM SUBRØUTINE FØR PRINTING RESULTS
6700PRINT"DRIVER RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6710PRINTR6,Q0*N1*N1*A3/W,N3,C6,(D(2,3)+A3)/A3
6720PRINT"PICKUP RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6730PRINTR7,Q0*N2*N2*A4/W,N4,C7,(F(2,3)+A4)/A4
6740PRINT "DRIVING VØLT","SERIES RES","AMP GAIN","INPUT IMP"
6750PRINTV0,R0,G5,R9
6760PRINT "DISCRIMINATØR VØLTAGE IS";V1
6770 PRINT
6780 PRINT L6,L6+L2,L6+2*L2,L6+3*L2,L6+4*L2
6790 FØR I=1 TØ 3
6800 PRINT
6810 PRINT M(I,1),M(I,2),M(I,3),M(I,4),M(I,5)
6820 PRINT P(I,1),P(I,2),P(I,3),P(I,4),P(I,5)
6830 PRINT Q(I,1),Q(I,2),Q(I,3),Q(I,4),Q(I,5)
6840 NEXT I
6850 RETURN
6999 REM SUBRØUTINE FØR AV. PHASE SHIFT AND LIFT-ØFF ERRØR
7000 Q1=Q(1,1)
7010 Q2=Q(1,1)
7020 FØR J=2 TØ 5
7030 IF Q(1,J)<Q1 THEN 7050
7040 Q1=Q(1,J)
7050 IF Q(1,J)>Q2 THEN 7070
7060 Q2=Q(1,J)
7070 NEXT J
7080 Q=(Q(1,1)+Q(1,2)+Q(1,3)+Q(1,4)+Q(1,5))/5
7090 Q=Q-(Q(3,1)+Q(3,2)+Q(3,3)+Q(3,4)+Q(3,5))/5
7092 Ø=Q
7100 PRINT"PHASE SHIFT";Q;"LIFT-ØFF";Q1-Q2;"%";100*(Q1-Q2)/Q
7110 PRINT "DEGREE";Q*P8,(Q1-Q2)*P8
7120 RETURN
7199 REM FØR CØIL DESIGN, ATTENUATØR, DRIFT, AND EXIT
7200PRINT"1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL"
7210INPUT N5
```

```
7220PRINT
72300N N5 GØ TØ 7300,8200,8600,9900
7299 REM FØR CØIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FØR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 GØ SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER";N3;"TURNS ØF #";G;"WIRE";
7390 PRINT Q7;"/LAYER";Q8;"LAYERS";R6;"ØHM"
7399 REM FØR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
7430 W2=R4
7440 W3=L4
7450 GØ SUB 7510
7460 N4=Q2
7470 R7=2*Q9
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIRE";
7490 PRINT Q7;"/LAYER";Q8;"LAYERS";R7;"ØHMS TØTAL"
7500 GØ TØ 1140
7509 REM SUBRØUTINE FØR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FØR GAGE
7540 G=Q1
7550 IF G>.5 THEN 7640
7560 Q5=.95*SQR((W2-W1)*W3/Q2)
7570 Q6=1.0371E-5/Q5/Q5
7580 G0=40
7590 G=40+10*(LØG(Q6)-LØG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 GØ TØ 7590
7630 G=INT(G)
7639 REM FØR TURN NUMBER AND R6
7640 Q6=(.9989+.017*(G/10-1))*10↑(G/10-4)
7650 Q5=SQR(1.0371E-5/Q6)
7660 IF G> 40 THEN 7690
7670 Q5=(.460655*LØG(Q5*1E3)-.43444)*1E-3+Q5
7680 GØ TØ 7700
7690 Q5=(98.02228*Q5+2.56791E-2)*1E-3+Q5
7700 Q7=INT(W3/Q5)
7710 Q8=INT((W2-W1)/Q5)
7720 IF Q2>.5 THEN 7740
7730 Q2=Q7*Q8
7740 Q9=Q2*Q6*(W2+W1)*P9/12
7750 RETURN
8199 REM FØR ATTENUATØR DESIGN
8200 PRINT "DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP"
8210 INPUT Q1,Q2,Q3,Q4
8220 IF Q1=0 THEN 8240
```

```
8230 R0=Q1
8240 IF Q2=0 THEN 8260
8250 C6=Q2
8260 IF Q3=0 THEN 8280
8270 R9=Q3
8280 IF Q4=0 THEN 8300
8290 C7=Q4
8300 Q1=Q0*N1*N1*(D(2,3)+A3)/W
8310 Q2=Q0*N2*N2*(F(2,3)+A4)/W
8320 PRINT "DVR CT";1/(W*SQR(Q1*C6));"BELØW RES";
8330 PRINT SQR(Q1/C6);"ØPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELØW RES";
8350 PRINT SQR(Q2/C7);"ØPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 GØ TØ 1140
8599 REM FØR DRIFTS
8600 PRINT"SYSTEM DRIFT VARIATIØNS"
8610 E1=.01
8620 E2=.01
8630 E3=.01
8640 E4=.01
8650 E7=.01
8660 E8=.01
8670 E9=.01
8680 A1=.01
8690 A2=.01
8700 A8=.01
8710 PRINT "% VARIATN","PARAMETER","RADIAN","DEGREE","% ØF RANGE"
8720 IF E1=0 THEN 8770
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 GØ SUB 9320
8760 R6=R6/(1+E1)
8770 IF E2=0 THEN 8820
8780 R7=R7*(1+E2)
8790 PRINT 100*E2,"PICKUP RES",
8800 GØ SUB 9320
8810 R7=R7/(1+E2)
8820 IF E3=0 THEN 8870
8830 C6=C6*(1+E3)
8840 PRINT 100*E3,"DVR SHUNT CAP",
8850 GØ SUB 9320
8860 C6=C6/(1+E3)
8870 IF E4=0 THEN 8920
8880 C7=C7*(1+E4)
8890 PRINT 100*E4,"P-U SHUNT CAP",
8900 GØ SUB 9320
8910 C7=C7/(1+E4)
8920 IF E7=0 THEN 8970
8930 R0=R0*(1+E7)
8940 PRINT 100*E7,"SERIES RES",
8950 GØ SUB 9320
8960 R0=R0/(1+E7)
8970 IF E8=0 THEN 9020
8980 R9=R9*(1+E8)
8990 PRINT 100*E8,"AMP INPUT RES",
9000 GØ SUB 9320
9010 R9=R9/(1+E8)
```

```
9020 IF E9=0 THEN 9070
9030 VO=VO*(1+E9)
9040 PRINT 100*E9,"APPLIED VØLT",
9050 GØ SUB 9320
9060 VO=VO/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 GØ SUB 9300
9110 F=F/(1+A1)
9120 IF A2=0 THEN 9170
9130 R5=R5*(1+A2)
9140 PRINT 100*A2,"MEAN RADIUS",
9150 GØ SUB 9300
9160 R5=R5/(1+A2)
9170 IF A8=0 THEN 9220
9180 K1=K1*(1+A8)
9190 PRINT 100*A8,"RESISTIVITY",
9200 GØ SUB 9300
9210 K1=K1/(1+A8)
9220 GØ TØ 7200
9299 REM SUBRØUTINE FØR DRIFT
9300 GØ SUB 600
9310 GØ SUB 1500
9320 GØ SUB 6000
9330 Q1=0
9340 FØR I=1 TØ3
9350 FØR J=1 TØ 5
9360 Q2=Ø1-ATN(Ø2/SQR(M(I,J)*M(I,J)-Ø2*Ø2))+P(I,J)-Q(I,J)
9370 IF ABS(Q1)>ABS(Q2) THEN 9390
9380 Q1=Q2
9390 NEXT J
9400 NEXT I
9410 PRINT Q1,180*Q1/P9,100*Q1/Ø
9420 RETURN
9900 END
```

RFCON, FORTRAN Version

The FORTRAN version of RFCON is very similar to the BASIC version. The line numbers given are only for identification and editing purposes and have no effect on the actual execution of the FORTRAN program. The input data for the program is contained in lines 250 through 480. The data must be typed in the seventh column, or six spaces must first be typed. The data are inputed as follows:

00250	R5 = (coil mean radius in inches)
00260	R1 = (normalized inner radius of driver coil)
00270	R2 = (normalized outer radius of driver coil)
00280	L3 = (normalized length of driver coil)
00290	R3 = (normalized inner radius of pickup coil)
00300	R4 = (normalized outer radius of pickup coil)
00310	L4 = (normalized length of pickup coil)
00320	L5 = (normalized length of recess of each pickup coil from the face of the driver coil)
00330	L6 = (normalized minimum lift-off of the driver coil)
00340	R6 = (resistance of driver coil in ohms)
00350	R7 = (resistance of both pickup coils in ohms)
00360	N3 = (number of turns on the driver coil)
00370	N4 = (number of turns on each pickup coil)
00380	R0 = (driver amplifier series resistance in ohms)
00390	R9 = (pickup amplifier shunt resistance in ohms)
00400	C6 = (shunt capacitance of driver circuit in farads)
00410	C7 = (shunt capacitance of pickup circuit in farads)
00420	V0 = (output voltage in volts)
00430	GAIN = (amplifier gain)
00440	FREQ = (operating frequency in Hertz)
00450	L2 = (normalized lift-off increment of the driver coil)
00460	RHO1 = (nominal electrical resistivity in microhm-cm)
00470	U1 = (relative magnetic permeability)
00480	M9 = (fractional variation of conductivity)

The print-out of the FORTRAN version of RFCON is practically identical to the BASIC version and will not be repeated. The main difference is that the question mark is not printed out when the program is ready to accept data. The Coil Design, Attenuator Design, Drift Check, and Continue Calculations options are the same. The line numbers, constant names, and parameter varied in the drift calculations are as follows:

Line Number	Constant	Parameter Varied
03120	DR1	Driver Resistance
03130	DR2	Pickup Resistance
03140	DR3	Driver Shunt Capacitance
03150	DR4	Pickup Shunt Capacitance
03160	DR5	Series Resistance
03170	DR6	Amplifier Input Resistance
03180	DR7	Applied Voltage
03190	DR8	Frequency
03200	DR9	Mean Radius
03210	DR10	Resistivity

For example, to vary the driver resistance by 2%, one would type:

```
03120        DR1 = 0.02
```

As in the BASIC version, the last three drifts require that the entire numerical integration be repeated and are relatively long running. If any of the drifts is set equal to zero, it will be omitted from the drift calculations.

Sample Calculation of RFCON.F4

Let us suppose that we wish to design a reflection type coil, identical to the one designed by the BASIC version. We put the following data in the program (generally by using the EDIT RECON.F4 command on the PDP-10 and inserting the statements). All linear dimensions are normalized by dividing by the coil mean radius, except the coil mean radius, which is in inches.

```
00250        R5 = .300
00260        R1 = .75
00270        R2 = 1.25
00280        L3 = .6
00290        R3 = .35
00300        R4 = .70
00310        L4 = .2
00320        L5 = 0.0
00330        L6 = .1
00340        R6 = 57.555
00350        R7 = 3443.01
00360        N3 = 810.0
00370        N4 = 2925.0
00380        R0 = 1.E6
00390        R9 = 1.E6
00400        C6 = 1.E-12
00410        C7 = 1.E-12
00420        V0 = 10.
00430        GAIN = 1.
00440        FREQ = 500.
00450        L2 = .025
00460        RHO1 = 2.95
00470        U1 = 1.0
00480        M9 = .05
```

The FORTRAN program may now be executed. The print-out will be essentially identical to the BASIC print-out and will not be repeated. The FORTRAN version of RFCON follows.

```
C IN THIS PRØGRAM, RHØ1 IS THE RESISTIVITY
C SIGMA IS THE GAMMA FACTØR
      CØMPLEX BETA1,BETA2,EX1,RNUM,DEN,SIGMA
      CØMPLEX TMUT,DRIVER,PICKUP
      REAL L3,L4,L5,L6,L2,N3,N4,M9,M9A,K1
      CØMMØN X,Z,Q1,PI/B1/R1,R2,R3,R4,L3,L4,R0,R6,R7
      CØMMØN /B1/R9,C6,C7,V0,GAIN,W,FREQ,R5,N3,N4
      CØMMØN /B2/TMUT,DRIVER,PICKUP,AIR1,AIR2/B3/GAGE,XIN
      CØMMØN /B3/XØUT,XLEN,TURNS,N1A,J1,PERLAY,XLAY
      DIMENSIØN RL(5),SIGMA(3),TMUT(3,5),DRIVER(3,5)
      DIMENSIØN PICKUP(3,5),TMAG(3,5),PHASE(3,5),SHIFT(3,5)
      EQUIVALENCE (RHØ1,K1),(GAIN,G5),(FREQ,F)
      PI=3.14159265
      RAD=180.0/PI
C
C
C
C
C
C
C
      JKL=0
C THE FØLLØWING ARE INPUT DATA FØR THE PARAMETERS ØF
C   THE CØILS, MATERIAL, AND CIRCUIT
      R5=.3
      R1=.75
      R2=1.25
      L3=.6
      R3=.35
      R4=.7
      L4=.2
      L5=0.0
      L6=.1
      R6=57.555
      R7=3443.01
      N3=810.0
      N4=2925.0
      R0=1.0E6
      R9=1.0E6
      C6=1.0E-12
      C7=1.0E-12
      V0=10.0
      GAIN=1.0
      FREQ=500.0
      L2=0.025
      RHØ1=2.95
      U1=1.0
      M9=.05
      M9A=200.0*M9
    5 W=2.0*PI*FREQ
      RM1=0.5094*U1*FREQ*R5*R5/RHØ1
C THE SYSTEM PARAMETERS ARE PRINTED ØUT
      IF(JKL.NE.0) GØ TØ 105
      TYPE 30,R1,R2,L3
   30 FØRMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
     1F8.5)
      TYPE 40,R3,R4,L4
```

```
   40 FØRMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
     1F8.5)
      TYPE 50,R5,FREQ
   50 FØRMAT(1H ,17HCØIL MEAN RADIUS=,F8.5,7H INCHES,3X,
     120HØPERATING FREQUENCY=,1PE12.5)
      TYPE 60,L5
   60 FØRMAT(1H ,15HPICKUP RECESSED,F8.5)
      TYPE 70,L6,L2
   70 FØRMAT(1H ,13HMIN LIFT-ØFF=,F8.5,3X,19HLIFT-ØFF INCREMENT=
     1F8.5)
      TYPE 80,U1,RM1,RHØ1
   80 FØRMAT(1H ,3HU1=,F6.2,5X,3HM1=,F9.5,2X,12HRESISTIVITY=,
     11PE12.5,11H MICRØHM CM)
      TYPE 90,M9A
   90 FØRMAT(1H ,23HCØNDUCTIVITY VARIATIØN=, F8.2,1H%)
C THE INTEGRATIØN IS PERFØRMED BY THE TRAPEZØIDAL METHØD,
C   EVALUATING AT THE CENTER ØF THE INTERVAL; FØR X LARGE
C   THE INTEGRAL CØNVERGES RAPIDLY,SØ LARGER INTERVALS
C   ARE TAKEN
C IN THE INTEGRATIØN TMUT, DRIVER, PICKUP, AIR1, AND
C   AIR2 ARE CALCULATED
  105 S1=0.01
      S2=5.0
      B1=0.0
      B2=S2
      AIR1=0.0
      AIR2=0.0
      DØ 108 J=1,3
      DØ 108 K=1,5
      DRIVER(J,K)=(0.0,0.0)
      PICKUP(J,K)=(0.0,0.0)
      TMUT(J,K)=(0.0,0.0)
  108 CØNTINUE
  110 I1=(B2-B1)/S1
      X=B1-S1/2.0
      DØ 170 M=1,I1
      X=X+S1
      Z=R2*X
      Q1=R2
C SUBRØUTINE BESSEL EVALUATES THE INTEGRAL ØF
C   THE PRØDUCT ØF THE BESSEL FUNCTIØN AND ITS
C   ARGUMENT
      CALL BESSEL(VAL2)
      Z=R1*X
      Q1=R1
      CALL BESSEL(VAL1)
      Z=R4*X
      Q1=R4
      CALL BESSEL(VAL4)
      Z=R3*X
      Q1=R3
      CALL BESSEL(VAL3)
      S3=S1*(VAL4-VAL3)*(VAL2-VAL1)
      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
      EX3=EXP(-X*L3)
      W1=1.0-EX3
      EX4=EXP(-X*L4)
```

```
      W2=1.0-EX4
      EX5=EXP(-X*L5)
      W3=EX3/(EX4*EX4*EX5*EX5)
      IF(X.GT.30.0) GØ TØ 160
C FRØM HERE THRØUGH LINE 130,SIGMA IS CALCULATED
      DØ 130 I=1,3
      RI=I-2
      RM=RM1*(1.0+RI*M9)
      BETA1=CSQRT(CMPLX(X*X,RM))/U1
  120 SIGMA(I)=(X-BETA1)/(X+BETA1)
  130 CØNTINUE
      EX2=EXP(-2.0*X*L2)
      EX6=EXP(-2.0*X*L6)
      W4=1.0-EX4*W3
      W5=EX5*EX6*W1*W2*W4
      W6=EX6*W1*W1
      W7=W2*W2*EX6*EX5*EX5*W4*W4
      RL(1)=1.0
      DØ 140 K=2,5
  140 RL(K)=EX2*RL(K-1)
      DØ 150 K=1,3
      DØ 150 L=1,5
      TMUT(K,L)=TMUT(K,L)+S3*W5*RL(L)*SIGMA(K)
      DRIVER(K,L)=DRIVER(K,L)+S4*W6*RL(L)*SIGMA(K)
  150 PICKUP(K,L)=PICKUP(K,L)+S5*W7*RL(L)*SIGMA(K)
  160 AIR1=AIR1+S4*2.0*(X*L3-W1)
      AIR2=AIR2+S5*(4.0*(X*L4-W2)-2.0*W2*W2*W3)
  170 CØNTINUE
      B1=B2
      B2=B2+S2
      S1=0.05
      IF(X.LT.9.0) GØ TØ 110
      S1=0.1
      IF(X.LT.29.0) GØ TØ 110
      S1=0.2
      IF(X.LT.39.0) GØ TØ 110
      S1=0.5
      IF(X.LT.79.0) GØ TØ 110
C THE INTEGRATIØN ENDS HERE
      IF(JKL.NE.0) GØ TØ 552
C NEXT THE PRØPERTIES ØF THE CØILS ARE DETERMINED AND PRINTED
  180 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
      CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
      TYPE 190
  190 FØRMAT(1H ,10HDRIVER RES,4X,10HINDUCTANCE,4X,8HNØ TURNS,
     16X,9HSHUNT CAP,5X,9HNØR IM PT)
      Q1=Q0*T1*T1*AIR1/W
      Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
      Q3=Q0*T2*T2*AIR2/W
      Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
      TYPE 200,R6,Q1,N3,C6,Q2
  200 FØRMAT(1H ,1PE12.5,2X,1PE12.5,2X,0PF8.1,6X,1PE12.5,2X,
     10PF9.6)
      TYPE 210
  210 FØRMAT(1H ,10HPICKUP RES,4X,10HINDUCTANCE,4X,8HNØ TURNS,
     16X,9HSHUNT CAP,5X,9HNØR IM PT)
      TYPE 200,R7,Q3,N4,C7,Q4
```

```
      TYPE 220
  220 FØRMAT(1H ,12HDRIVING VØLT,2X,10HSERIES RES,4X,
     18HAMP GAIN,6X,9HINPUT IMP)
      TYPE 230,VO,RO,GAIN,R9
  230 FØRMAT(1H ,F5.1,9X,1PE12.5,2X,OPF8.1,6X,1PE12.5)
      TYPE 240,V1
  240 FØRMAT(1H ,22HDISCRIMINATØR VØLTAGE=,1PE12.5)
      TYPE 250
  250 FØRMAT(1H )
      RL(1)=L6
      DØ 260 I=2,5
  260 RL(I)=L2+RL(I-1)
      TYPE 270,RL
  270 FØRMAT(1H ,4(F6.3,8X),F6.3)
      TYPE 250
C THE VØLTAGE MAGNITUDE,PHASE,AND SHIFT ARE PRINTED FØR
C   THE VARIØUS LIFT-ØFF VALUES
      DØ 280 I=1,3
      TYPE 290,(TMAG(I,J),J=1,5)
      TYPE 290,(PHASE(I,J),J=1,5)
      TYPE 290,(SHIFT(I,J),J=1,5)
      TYPE 250
  280 CØNTINUE
  290 FØRMAT(1H ,4(1PE12.5,2X),1PE12.5)
      CALL SENS(SHIFT,RAD,SEN)
C THE USER SELECTS ØNE ØF FØUR PØSSIBILITIES
  295 TYPE 300
  300 FØRMAT(' 1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK
     1  4 CØN CAL')
      TYPE 250
      ACCEPT 310,N5
  310 FØRMAT(I1)
      GØ TØ(320,450,540,690),N5
C THE FIRST PØSSIBILITY PRINTS FACTØRS IN THE  CØIL
C   DESIGN; USER INPUTS INTEGER DATA AS REQUESTED
  320 TYPE 330
  330 FØRMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
     1PTURNS')
      TYPE 250
      ACCEPT 340,N1A,N2A,N3A,N4A
  340 FØRMAT(4I)
      IF (N1A*N2A.EQ.0) GØ TØ 350
      GAGE=N1A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      TURNS=N2A
      N3=N2A
      N1A=-1
      J1=1
      CALL GAGER(R6)
      GØ TØ 370
  350 IF(N1A.EQ.0) GØ TØ 360
      GAGE=N1A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=1
```

```
      CALL GAGER(R6)
      N3=TURNS
      GØ TØ 370
  360 IF(N2A.EQ.0) GØ TØ 390
      N3=N2A
      TURNS=N2A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=0
      CALL GAGER(R6)
  370 TYPE 380,TURNS,GAGE,PERLAY,XLAY,R6
  380 FØRMAT(1H ,6HDRIVER,F6.1,10H TURNS ØF#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  390 IF(N3A*N4A.EQ.0) GØ TØ 400
      GAGE=N3A
      TURNS=N4A
      N4=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      R7=2.0*R7
      GØ TØ 420
  400 IF(N3A.EQ.0) GØ TØ 410
      GAGE=N3A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      N4=TURNS
      R7=2.0*R7
      GØ TØ 420
  410 IF(N4A.EQ.0) GØ TØ 440
      N4=N4A
      TURNS=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=0
      CALL GAGER(R7)
      R7=2.0*R7
  420 TYPE 430,TURNS,GAGE,PERLAY,XLAY,R7
  430 FØRMAT(1H ,6HPICKUP,F6.1,10H TURNS EA#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  440 GØ TØ 180
C THE SECØND PØSSIBILITY DEALS WITH ATTENUATØR DESIGN;
C     USER INPUTS REQUESTED DATA IN E FIELD TYPE
  450 TYPE 460
  460 FØRMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
     1 SHUNT CAP')
      TYPE 250
      ACCEPT 470,P1,P2,P3,P4
  470 FØRMAT(4E)
      IF(P1.EQ.0.0) GØ TØ 480
      R0=P1
```

```
480 IF(P2.EQ.0.0) GØ TØ 490
    C6=P2
490 IF(P3.EQ.0.0) GØ TØ 500
    R9=P3
500 IF(P4.EQ.0.0) GØ TØ 510
    C7=P4
510 Q5=1.0/(W*SQRT(Q1*Q2*C6))
    Q6=SQRT(Q1*Q2/C6)
    Q7=R0/(W*Q1*Q2)
    Q8=1.0/(W*SQRT(Q3*Q4*C7))
    Q9=SQRT(Q3*Q4/C7)
    Q10=R9/(W*Q3*Q4)
    TYPE 520,Q5,Q6,Q7
520 FØRMAT(1H ,7HDVR CKT,1PE12.5,10H BELØW RES,1PE12.5,
   18H ØPT RES,1PE12.5,11H RES/REACT.)
    TYPE 530,Q8,Q9,Q10
530 FØRMAT(1H ,7HP-U CKT,1PE12.5,10H BELØW RES,1PE12.5,
   18H ØPT RES,1PE12.5,11H RES/REACT.)
    GØ TØ 180
C THE THIRD PØSSIBILITY EXAMINES THE EFFECTS ØF DRIFT
C   ØN THE SYSTEM
540 TYPE 550
550 FØRMAT(1H ,23HSYSTEM DRIFT VARIATIØNS)
    DR1=0.01
    DR2=0.01
    DR3=0.01
    DR4=0.01
    DR5=0.01
    DR6=0.01
    DR7=0.01
    DR8=0.01
    DR9=0.01
    DR10=0.01
    GØ TØ 559
552 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
    GØ TØ (675,678,681), JKL
559 TYPE 560
560 FØRMAT(1H ,11H% VARIATIØN,3X,13HPARAMETER VAR,1X,
   17HRADIANS,7X,7HDEGREES,7X,10H% ØF RANGE)
    IF(DR1.EQ.0.0) GØ TØ 580
    R6=R6*(1.0+DR1)
    DR100=100.0*DR1
    TYPE 570,DR100
570 FØRMAT(1H ,F4.1,10X,13HDRIVER RES    $)
    CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
    R6=R6/(1.0+DR1)
580 IF(DR2.EQ.0.0) GØ TØ 600
    R7=R7*(1.0+DR2)
    DR100=100.0*DR2
    TYPE 590,DR100
590 FØRMAT(1H ,F4.1,10X,13HPICKUP RES    $)
    CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
    R7=R7/(1.0+DR2)
600 IF(DR3.EQ.0.0) GØ TØ 620
    C6=C6*(1.0+DR3)
    DR100=100.0*DR3
    TYPE 610,DR100
610 FØRMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
```

```
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      C6=C6/(1.0+DR3)
  620 IF(DR4.EQ.0.0) GØ TØ 640
      C7=C7*(1.0+DR4)
      DR100=100.0*DR4
      TYPE 630,DR100
  630 FØRMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      C7=C7/(1.0+DR4)
  640 IF(DR5.EQ.0.0) GØ TØ 660
      R0=R0*(1.0+DR5)
      DR100=100.0*DR5
      TYPE 650,DR100
  650 FØRMAT(1H ,F4.1,10X,13HSERIES RES    $)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R0=R0/(1.0+DR5)
  660 IF(DR6.EQ.0.0) GØ TØ 671
      R9=R9*(1.0+DR6)
      DR100=100.0*DR6
      TYPE 670,DR100
  670 FØRMAT(1H ,F4.1,10X,13HAMP INPUT RES$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R9=R9/(1.0+DR6)
  671 IF(DR7.EQ.0.0) GØ TØ 673
      V0=V0*(1.0+DR7)
      DR100=100.0*DR7
      TYPE 672,DR100
  672 FØRMAT(1H ,F4.1,10X,13HAPPLIED VØLT.$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      V0=V0/(1.0+DR7)
  673 IF(DR8.EQ.0.0) GØ TØ 676
      FREQ=FREQ*(1.0+DR8)
      DR100=100.0*DR8
      TYPE 674,DR100
  674 FØRMAT(1H ,F4.1,10X,13HFREQUENCY    $)
      JKL=1
      GØ TØ 5
  675 FREQ=FREQ/(1.0+DR8)
      JKL=0
  676 IF(DR9.EQ.0.0) GØ TØ 679
      R5=R5*(1.0+DR9)
      DR100=100.0*DR9
      TYPE 677,DR100
  677 FØRMAT(1H ,F4.1,10X,13HMEAN RADIUS  $)
      JKL=2
      GØ TØ 5
  678 R5=R5/(1.0+DR9)
      JKL=0
  679 IF(DR10.EQ.0.0) GØ TØ 295
      RHØ1=RHØ1*(1.0+DR10)
      DR100=100.0*DR10
      TYPE 680,DR100
  680 FØRMAT(1H ,F4.1,10X,13HRESISTIVITY  $)
      JKL=3
      GØ TØ 5
  681 RHØ1=RHØ1/(1.0+DR10)
      JKL=0
      GØ TØ 295
```

```
C THE FØURTH PØSSIBILITY ENDS CALCULATIØNS
  690 CALL EXIT
      END
      SUBRØUTINE BESSEL(VAL)
      CØMMØN X,Z,Q1,PI
      IF(Z.GT.5.0) GØ TØ 1010
      K=2.0*Z
      L=K+3
      F1=0.5*Q1*Q1*Q1
      VAL=F1/3.0
      DØ 1000 I=1,L
      AI=I
      F1=-F1*0.25*Z*Z/(AI*AI+AI)
      VAL=VAL+F1/(2.0*AI+3.0)
 1000 CØNTINUE
      GØ TØ 1020
 1010 X0=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
      X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
      X1=(((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
      X1=(X1-0.187344E-2)/Z+0.7979095
      VAL=(1.0-SQRT(Z)*(X1*CØS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
     1(X*X*X)
 1020 RETURN
      END
      SUBRØUTINE PHASET(A,B,C,V1,Ø3)
      DIMENSIØN A(3,5),B(3,5),C(3,5)
      Ø1=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
      Ø2=-(A(2,5)*CØS(B(2,5))-A(2,1)*CØS(B(2,1)))
      Ø3=ATAN2(Ø1,Ø2)
      V1=A(2,1)*SIN(Ø3+B(2,1))
      DØ 2000 I=1,3
      DØ 2000 J=1,5
 2000 C(I,J)=Ø3-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(I,J)
      RETURN
      END
      SUBRØUTINE SENS(Ø,RAD,Ø1)
      DIMENSIØN Ø(3,5)
      Ø9=Ø(1,1)
      Ø0=Ø(1,1)
      DØ 3010 I=2,5
      IF(Ø(1,I).LT.Ø9) GØ TØ 3000
      Ø9=Ø(1,I)
 3000 IF(Ø(1,I).GT.Ø0) GØ TØ 3010
      Ø0=Ø(1,I)
 3010 CØNTINUE
      Ø1=(Ø(1,1)+Ø(1,2)+Ø(1,3)+Ø(1,4)+Ø(1,5))/5.0
      Ø1=Ø1-(Ø(3,1)+Ø(3,2)+Ø(3,3)+Ø(3,4)+Ø(3,5))/5.0
      XLØ=Ø9-Ø0
      PERCT=100*XLØ/Ø1
      DEGR1=Ø1*RAD
      DEGR2=XLØ*RAD
      TYPE 3020,Ø1,XLØ,PERCT
 3020 FØRMAT(1H ,12HPHASE SHIFT=,1PE12.5,2X,8HLIFTØFF=,
     11PE12.5,2X,2H%=,1PE12.5)
      TYPE 3030,DEGR1,DEGR2
 3030 FØRMAT(1H ,7HDEGREE:,1PE13.5,5X,1PE13.5)
      RETURN
      END
```

```
      SUBRØUTINE GAGER(RES)
      CØMMØN /B3/G,D1,D2,RLN,T5,N1,J1,D,E
      PI=3.1415926536
      IF(J1.EQ.1) GØ TØ 4015
      N1=-1
      D3=0.95*SQRT((D2-D1)*RLN/T5)
      X2=1.0371E-5/(D3*D3)
      Q=40.0
 4000 G=40.0+10.0*(ALØG(X2)-ALØG(.9989+.017*(Q/10.0-1.0)))/2.3
     10259
      IF(ABS(Q-G).LT.1.0E-4) GØ TØ 4010
      Q=G
      GØ TØ 4000
 4010 IG=G
      G=IG
 4015 X2=(.9989+.017*(G/10.0-1.0))*10.0**(G/10.0-4.0)
      D3=SQRT(1.0371E-5/X2)
      IF(G.GT.40.0) GØ TØ 4020
      X3=(.460655*ALØG(D3*1.E3)-.43444)*1.E-3
      GØ TØ 4030
 4020 X3=(98.02228*D3+2.56791E-2)*1.E-3
 4030 ID=(RLN/(D3+X3))
      D=ID
      IE=(D2-D1)/(D3+X3)
      E=IE
      IF(N1.EQ.-1) GØ TØ 4040
      T5=D*E
 4040 RES=T5*X2*(D2+D1)*PI/12.0
      RETURN
      END
      SUBRØUTINE CIRCT(TMAG,PHASE,Q0,T1,T2)
      CØMMØN /B1/R1,R2,R3,R4,RL3,RL4,R0,R6,R7,R9,C6,C7,V0,GAIN
      CØMMØN /B1/W,FREQ,RBAR,TURNS1,TURNS2/B2/TMUT,DRIVER
      CØMMØN /B2/PICKUP,AIR1,AIR2
      CØMPLEX TMUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
      CØMPLEX DENØM,TNUM,VØLT
      DIMENSIØN TMUT(3,5),DRIVER(3,5),PICKUP(3,5)
      DIMENSIØN TMAG(3,5),PHASE(3,5)
      T1=TURNS1/((R2-R1)*RL3)
      T2=TURNS2/((R4-R3)*RL4)
      Q0=6.300475204E-7*FREQ*RBAR
      Z1=CMPLX(W*R0*C6,-1.0)
      Z2=CMPLX(W*R9*C7,-1.0)
      Z3=CMPLX(0.0,-R0)
      Z4=CMPLX(0.0,-R9)
      DØ 5000 I=1,3
      DØ 5000 J=1,5
      Z5=Q0*T1*T2*TMUT(I,J)
      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(I,J)+AIR1)
      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
      DENØM=Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*
     3 (Z2*(Z7+R7)+Z4)
      TNUM=V0*R9*GAIN*(0.0,-1.0)*Z5
      VØLT=TNUM/DENØM
      TMAG(I,J)=CABS(VØLT)
 5000 PHASE(I,J)=ATAN2(AIMAG(VØLT),REAL(VØLT))
      RETURN
```

```
      END
      SUBRØUTINE CIRCT1(Ø1,V1,Ø,RAD,SEN)
      DIMENSIØN Ø(3,5),TMAG(3,5),PHASE(3,5)
      CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
      Q1=0.0
      DØ 6000 I=1,3
      DØ 6000 J=1,5
      Q2=Ø1-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
     1+PHASE(I,J)-Ø(I,J)
      IF(ABS(Q1).GT.ABS(Q2)) GØ TØ 6000
      Q1=Q2
 6000 CØNTINUE
      Q2NEW=RAD*Q1
      Q3=100.0*Q1/SEN
      TYPE 6010,Q1,Q2NEW,Q3
 6010 FØRMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
      RETURN
      END
```

REFLECTION COIL ABOVE A CLAD CONDUCTOR

We shall now consider the case of a reflection coil above a clad conductor. This program calculates the magnitude and phase of the voltage that is fed to the phase measuring circuits of the phase-sensitive eddy-current instrument and is designed to help analyze eddy-current measurements of cladding thickness.

The program calculates the magnitude and phase of the induced voltage for five different values of lift-off with each of three different cladding thickness values, for a total of fifteen calculations. This allows one to examine the sensitivity to lift-off variations as well as cladding thickness variations. In addition, the program also calculates the phase shift with the discriminator adjusted to give the same phase on the nominal cladding thickness sample with maximum and minimum lift-off. The phase on the nominal sample with minimum lift-off is taken as zero, and all other phase shifts are measured relative to it. The equations that are evaluated are Eq. (8) for the mutual coupling, Eq. (9) for the driver coil impedance, and Eq. (17) for the pickup coil impedance. The gamma factor for the clad conductor is given in Eq. (33). The programs are written in both BASIC and FORTRAN for use on a PDP-10. The BASIC program follows.

To use this program, one must first divide all coil and lift-off dimensions by the mean radius of the driver coil. Then the following lines must be typed into the program:

```
250     R5 = (numerical value of driver coil mean radius in inches)
260     R1 = (numerical value of normalized driver coil inner radius)
270     R2 = (numerical value of normalized driver coil outer radius)
280     L3 = (numerical value of normalized driver coil length)
290     R3 = (numerical value of normalized pickup coil inner radius)
300     R4 = (numerical value of normalized pickup coil outer radius)
310     L4 = (numerical value of normalized pickup coil length)
320     L5 = (numerical value of normalized pickup recess from face
             of driver)
330     L6 = (numerical value of normalized driver coil minimum
             lift-off)
```

340 R6 = (numerical value of resistance of driver coil in ohms)

350 R7 = (numerical value of total resistance of both pickup coils in ohms)

360 N3 = (number of turns on driver coil)

370 N4 = (number of turns on each pickup coil)

380 R0 = (output series resistance of driving amplifier in ohms)

390 R9 = (input shunt resistance of pickup amplifier in ohms)

400 C6 = (total shunt capacitance of driving circuit in farads)

410 C7 = (total shunt capacitance of pickup circuit in farads)

420 V0 = (output voltage of driving amplifier in volts)

430 G5 = (gain of pickup amplifier)

440 F = (operating frequency in Hertz)

450 L2 = (numerical value of normalized driver coil lift-off increment)

510 C(1) = (numerical value of minimum cladding thickness in inches)

520 C(2) = (numerical value of nominal cladding thickness in inches)

530 C(3) = (numerical value of maximum cladding thickness in inches)

540 K1 = (numerical value of resistivity of base material in microhm-cm)

545 U1 = (numerical value of relative permeability of base material)

550 K2 = (numerical value of resistivity of cladding material in microhm-cm)

555 U2 = (numerical value of relative permeability of cladding material)

The program may now be run. The print-out by the computer will have the following format:

```
R1= (R1)       R2= (R2)          DRIVER LENGTH IS (L3)
R3= (R3)       R4= (R4)          PICK UP LENGTH IS (L4)
COIL MEAN RADIUS  (R5)           INCHES     OPERATING FREQUENCY (F)
PICK UP RECESSED  (L5)
MINIMUM LIFT-OFF  (L6) LIFT-OFF INCREMENT  (L2)
U1= (U1)       M1= .....         RESISTIVITY= (K1)   MICROHM CM
U2= (U2)       M2= .....         RESISTIVITY= (K2)   MICROHM CM
THICKNESS= (C(1))                  (C(2))         (C(3))
DRIVER RES     INDUCTANCE        NO TURNS       SHUNT CAP       NOR IM PT
  (R6)           ......            (N3)           (C6)            .......
PICKUP RES     INDUCTANCE        NO TURNS       SHUNT CAP       NOR IM PT
  (R7)           ......            (N4)           (C7)            ......
DRIVING VOLT   SERIES RES        AMP GAIN       INPUT IMP
  (V0)           (R0)              (G5)           (R9)
DISCRIMINATOR VOLTAGE IS ......

  (L6)           (L6+L2)         (L6+2L2)        (L6+3L2)        (L6+4L2)

 .....           .....            .....           .....           .....
 .....           .....            .....           .....           .....
 .....           .....            .....           .....           .....

 .....           .....            .....           .....           .....
 .....           .....            .....           .....           .....
  0              .....            .....           .....           .....

 .....           .....            .....           .....           .....
 .....           .....            .....           .....           .....
 .....           .....            .....           .....           .....
PHASE SHIFT .....  LIFT-OFF .....                 %.....
DEGREE .....                .....
1 COIL DESIGN   2 ATTEN. DESIGN   3 DRIFT CHECK   4 CON CAL
 ?4
```

The various symbols enclosed in parentheses are used to indicate that the numerical value of the symbol will be printed.

There are five columns of data, one under each value of lift-off. Each column is divided into three sections of three lines each. These sections correspond, from top to bottom, to the three values of cladding thickness. The three lines in each section are, from top to bottom, the magnitude of the voltage out of the pickup amplifier, the phase shift between the voltage out of the pickup amplifier and the driving voltage, and the phase shift between the voltage out of the pickup amplifier with the discriminator set to give the same phase shift with minimum lift-off and maximum lift-off on the C(2) cladding thickness sample. This sample is usually (but does not have to be) the nominal thickness. The phase shift in the third line is always measured from the C(2) cladding thickness sample with minimum lift-off. The voltage out of the pickup amplifier will be in volts and be either peak-to-peak or RMS, whichever is used for VO, the output voltage of the driving amplifier. The value of the dimensionless product $R_5^2\omega\mu_1\sigma_1$ is also calculated and printed out as M1 = $(R_5^2\omega\mu_1\sigma_1)$ and likewise M2 is calculated using $R_5^2\omega\mu_2\sigma_2$. The inductance in henries of the driving coil in air and the normalized imaginary part of the driving coil impedance are also printed, with C(2) cladding thickness and nominal lift-off (L6+2L2). The inductance in henries of both pickup coils in air and the normalized imaginary part of the pickup coils' impedance with cladding thickness C(2) and lift-off are also printed. The total phase shift for the cladding thickness variation between C(3) and C(1), the maximum phase shift due to lift-off, and the maximum percent of range error in cladding thickness measurements due to lift-off are given. The phase shifts are given first in radians and then in degrees.

The program then enters a branching loop that allows the following options, depending on which of 1, 2, 3, or 4 is typed as input after the question mark.

1. Coil Design

If a 1 is typed by the operator after the question mark, the program will enter the Coil Design Loop. This loop will allow the number of turns on the driver and pickup coils to be varied. The loop will allow the wire gage to be given and then calculate the number of turns and coil resistance, or it will allow the number of turns to be entered and calculate the gage and coil resistance, or both turns and gage can be entered. If zeros are entered for both the gage and turns of either the driver or pickup coils, the present value of these will be retained. The program then starts with the label

DRIVER RES INDUCTANCE NO TURNS SHUNT CAP NOR IM PT ,

and the remainder of the program is recalculated and printed, with the "new" coil in the circuit. However, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

2. Attenuator Design

This loop will allow the driver series resistance, R0, the driver shunt capacitance, C6, the amplifier input impedance, R9, and the shunt capacitance in the pickup circuit, C7, to be varied. If a 2 is typed after the question mark, the computer will respond with

DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, CHUNT CAP .

The resistance is to be given in ohms, and the capacitance in farads. If zero is typed in for any value, the present value in the computer will be retained. After the input data and a carriage return are typed, the computer will calculate the ratio of resonant frequency to operating frequency for the particular L-C circuit, a very rough value of resistance for minimum temperature drift, and the ratio between the resistance and reactance in the circuit for both the driver and pickup circuits. The program then starts with the label

DRIVER RES INDUCTANCE NO TURNS SHUNT CAP NOR IM PT ,

and the remainder of the program is recalculated and printed with the "new" attenuator in the circuit. Again, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

3. Drift Check

This loop calculates the effect of the drift of any of the circuit or sample parameters after the instrument has been calibrated and adjusted. If a 3 is typed as input, the program will respond with the percent variation, the parameter varied, the maximum change in phase (both radians and degrees) of any of the 15 different phases calculated (5 lift-off values for each of 3 different cladding thickness values) and the percent of the range represented by the drift. The percent variation of each parameter may be varied independently. The following table gives the parameter, the line number, and the constant to be varied:

Parameter	Line Number	Constant
Driver Resistance	8610	E1
Pickup Resistance	8620	E2
Driver Shunt Cap.	8630	E3
Pickup Shunt Cap.	8640	E4
Series Resistance	8650	E7
Amp. Input Resistance	8660	E8
Applied Voltage	8670	E9
Frequency	8680	A1
Mean Radius	8690	A2
Base Resistivity	8700	A8
Cladding Resistivity	8705	A9

For example, to put in a 2% variation in the driver coil resistance, one would type:

8610 E1 = .02

The amount that each parameter is varied must be set before the program is run. All of the variations are 0.01 or 1% in the current version of the program. Since the phase shift produced by the parameter variation is quite linear over a range of about 10%, a linear interpolation or extrapolation may be used from the 1% parameter variation. If zero is typed in for any parameter variation, that parameter will not be varied nor will it be typed out in the list of parameter variations. When the calculation is completed and the drifts printed, the program returns to the branch point and repeats the question

1 Coil Design 2 Atten. Design 3 Drift Check 4 Con Cal .

The first seven drifts do not require repetition of the numerical integrations to calculate M, Z_{DR}, and Z_{PU}, but they must be repeated to calculate the drifts due to frequency, mean radius, and resistivity changes of the base and cladding materials. Therefore, the calculation of these last four drifts requires a considerable amount of computer time.

4. Con Cal

This loop is to continue calculations. If a series of calculations is to be made, a loop may be established at this point. However, in the present version of the program, if a 4 is typed as input, the program will end.

Sample Calculation of RFCLAD

Let us suppose we wish to design a reflection-type coil to measure the thickness of aluminum with a resistivity of 3.632 μΩ-cm clad on aluminum with a resistivity of 5.393 μΩ-cm. From another report[10] we have determined that the following parameters give near optimum performance for a nominal cladding thickness of 0.028 in. The driver coil has a mean radius of 0.08325 in., inner and outer radii of 0.0625 and 0.104 in., and a length of 0.030 in. The pickup coils have inner and outer radii of 0.030 and 0.058 in., a length of 0.008 in., and are mounted flush with the ends of the driver coil. The driver coil has 360 turns of No. 46 wire with a resistance of 79.36 Ω, and the pickup coils have 410 turns each of No. 54 wire, with a resistance of 530.5 Ω for both coils. The driver series and the pickup amplifier input resistances are both chosen to be 1 MΩ. The shunt capacitances in both circuits are chosed to be 1 pF. This corresponds to practically infinite source and detector impedances, so that only the mutual coupling, M, affects the phases. The minimum lift-off is taken to be 0.0083 in. with a lift-off increment of 0.002 in. The nominal cladding thickness is 0.028 in., with the minimum and maximum thicknesses 0.0266 and 0.0294 in. The relative magnetic permeability is 1 for both cladding and base material. The frequency is 10 KHz; the output voltage of the driving amplifier is 10 V, and the gain of the pickup amplifier is unity (a unity gain allows the actual gain needed in the amplifier to be calculated by dividing the maximum output voltage with unity gain into 10).

The program RFCLAD is assumed to be in the active core, and the following information is typed into the computer. All linear dimensions are normalized by dividing by the coil mean radius, except for the coil mean radius, which is in inches.

---

[10] C. V. Dodd and W. A. Simpson, *Thickness Measurements Using Eddy-Current Techniques*, ORNL-TM-3712 (March 1972).

```
250     R5 = .08325
260     R1 = .75
270     R2 = 1.25
280     L3 = .36
290     R3 = .36
300     R4 = .696
310     L4 = .096
320     L5 = 0
330     L6 = .1
340     R6 = 79.36
350     R7 = 530.5
360     N3 = 360
370     N4 = 410
380     R0 = 1E6
390     R9 = 1E6
400     C6 = 1E-12
410     C7 = 1E-12
420     V0 = 10
430     G5 = 1
440     F = 1E4
450     L2 = .025
510     C(1) = .0266
520     C(2) = .028
530     C(3) = .0294
540     K1 = 5.39261
545     U1 = 1
550     K2 = 3.63204
555     U2 = 1
```

The program may now be run with the following results. The data inputed from the terminal by the user are underlined. A carriage return must be typed by the user at the end of each input line.

```
RFCLAD(BASIC)

R1= 0.75        R2= 1.25        DRIVER LENGTH IS 0.36
R3= 0.36        R4= 0.696       PICK UP LENGTH IS 0.096
CØIL MEAN RADIUS 8.32500E-2 INCHES      ØPERATING FREQUENCY 10000
PICK UP RECESSED 0
MIN LIFT-ØFF= 0.1 LIFT-ØFF INCREMENT= 0.025
U1= 1           M1= 6.54632     RESISTIVITY= 5.393 MICRØHM CM
U2= 1           M2= 9.72034     RESISTIVITY= 3.632 MICRØHM CM
THICKNESS=       0.0266          0.028          0.0294
DRIVER RES      INDUCTANCE      NØ TURNS       SHUNT CAP       NØR IM PT
  79.36           6.05067E-4     360            1.00000E-12    0.849616
PICKUP RES      INDUCTANCE      NØ TURNS       SHUNT CAP       NØR IM PT
 530.5           4.72124E-4      410           1.00000E-12    0.992308
DRIVING VØLT    SERIES RES      AMP GAIN       INPUT IMP
 10              1000000         1              1000000
DISCRIMINATØR VØLTAGE IS-6.34032E-7

 0.1             0.125           0.15           0.175           0.2

 1.31981E-5      1.21111E-5      1.11162E-5     1.02067E-5      9.37605E-6
-0.802612       -0.806756       -0.811478      -0.816682       -0.822287
 3.52982E-3      3.70341E-3      3.67419E-3     3.56174E-3      3.47080E-3

 1.32201E-5      1.21309E-5      1.11340E-5     1.02228E-5      9.39060E-6
-0.806062       -0.810183       -0.814883      -0.820067       -0.825653
 0               1.91204E-4      1.77376E-4     7.86185E-5      0

 1.32375E-5      1.21466E-5      1.11481E-5     1.02355E-5      9.40207E-6
-0.809286       -0.813384       -0.818065      -0.82323        -0.828798
-3.28660E-3     -3.07812E-3     -3.07631E-3    -3.16127E-3     -3.22730E-3
PHASE SHIFT 6.75391E-3 LIFT-ØFF 2.32607E-4 IN % 3.44404
IN DEGREE 0.386971              1.33274E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?1
```

```
DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS
 ?46,0,54,0
DRIVER 391 TURNS ØF # 46 WIRE 17 /LAYER 23 LAYERS 71.9293 ØHM
PICKUP 429 TURNS EA # 54 WIRE 11 /LAYER 39 LAYERS 532.582 ØHMS TØTAL
DRIVER RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 71.9293       7.13760E-4     391            1.00000E-12    0.849616
PICKUP RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 532.582       5.16896E-4     429            1.00000E-12    0.992308
DRIVING VØLT   SERIES RES     AMP GAIN       INPUT IMP
 10            1000000        1              1000000
DISCRIMINATØR VØLTAGE IS-7.20554E-7

 0.1            0.125          0.15           0.175          0.2

 1.49990E-5     1.37637E-5     1.26329E-5     1.15994E-5     1.06554E-5
-0.80262       -0.806764      -0.811486      -0.81669       -0.822296
 3.52983E-3     3.70337E-3     3.67417E-3     3.56171E-3     3.47078E-3

 1.50239E-5     1.37861E-5     1.26532E-5     1.16177E-5     1.06719E-5
-0.80607       -0.810191      -0.814891      -0.820075      -0.825662
 0              1.91189E-4     1.77346E-4     7.85962E-5     0

 1.50438E-5     1.38040E-5     1.26693E-5     1.16321E-5     1.06850E-5
-0.809294      -0.813393      -0.818073      -0.823238      -0.828806
-3.28659E-3    -3.07814E-3    -3.07633E-3    -3.16130E-3    -3.22733E-3
PHASE SHIFT 6.75391E-3 LIFT-ØFF 2.32592E-4 IN % 3.44382
IN DEGREE 0.386971             1.33266E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?2
```

```
DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP
 ?5.2E2,4.7E-9,5.9E2,5.3E-9
DVR CT 9.42723 BELØW RES 359.202 ØPT RES 13.6474 RES/REACTANCE
P-U CT 9.6529 BELØW RES 311.091 ØPT RES 18.3072 RES/REACTANCE
DRIVER RES     INDUCTANCE    NØ TURNS      SHUNT CAP     NØR IM PT
 71.9293        7.13760E-4    391           4.70000E-9    0.849616
PICKUP RES     INDUCTANCE    NØ TURNS      SHUNT CAP     NØR IM PT
 532.582        5.16896E-4    429           5.30000E-9    0.992308
DRIVING VØLT   SERIES RES    AMP GAIN      INPUT IMP
 10             520           1             590
DISCRIMINATØR VØLTAGE IS-7.33995E-4

 0.1            0.125         0.15          0.175         0.2

 1.32547E-2     1.21734E-2    1.11820E-2    1.02743E-2    9.44413E-3
-1.00731       -1.01222      -1.01766      -1.02353      -1.02975
 3.49638E-3     3.51010E-3    3.43129E-3    3.37805E-3    3.45436E-3

 1.32771E-2     1.21936E-2    1.12002E-2    1.02907E-2    9.45898E-3
-1.01071       -1.01561      -1.02102      -1.02687      -1.03308
 0              2.67476E-5   -4.10676E-5   -8.47280E-5    0

 1.32949E-2     1.22096E-2    1.12146E-2    1.03037E-2    9.47072E-3
-1.0139        -1.01877      -1.02417      -1.03         -1.03619
-3.25632E-3    -3.21634E-3   -3.27227E-3   -3.30567E-3   -3.21174E-3
PHASE SHIFT 6.70650E-3 LIFT-ØFF 1.32054E-4 IN % 1.96905
IN DEGREE 0.384255           7.56615E-3
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?3

SYSTEM DRIFT VARIATIØNS
% VARIATN      PARAMETER     RADIAN        DEGREE        % ØF RANGE
 1             DRIVER RES    -1.75685E-5   -1.00660E-3   -0.261962
 1             PICKUP RES    -7.94083E-5   -4.54976E-3   -1.18405
 1             DVR SHUNT CAP -2.11865E-4   -0.012139     -3.15909
 1             P-U SHUNT CAP -9.27642E-4   -5.31500E-2   -13.832
 1             SERIES RES     1.21604E-3    6.96740E-2    18.1322
 1             AMP INPUT RES -6.56098E-4   -3.75917E-2   -9.78301
 1             APPLIED VØLT  -7.71806E-4   -4.42212E-2   -11.5083
 1             FREQUENCY     -6.12591E-3   -0.350989     -91.3429
 1             MEAN RADIUS   -7.56684E-3   -0.433548     -112.828
 1             BASE RESISTVY  8.27610E-4    4.74186E-2    12.3404
 1             CLADDING RES   2.59832E-3    0.148873      38.7432
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?4
```

The user has exercised all the design options available, and these options may be repeated, omitted, or taken in any order. The BASIC version of the program RFCLAD follows.

```
1   REM RFCLAD(BASIC)
10 REM REFLECTIØN CØIL FØR CLADDING THICKNESS
40 DIM A(3,5),B(3,5),C(3,5),D(3,5),E(3,5),F(3,5)
50 DIM M(3,5),P(3,5),Q(3,5)
199 REM CØNSTANT
200 P9=3.14159
210 P8=180/P9
249 REM CØIL DATA
250R5=.08325
260R1=.75
270R2=1.25
280L3=.36
290R3=.36
300R4=.696
310L4=.096
320L5=0
330L6=.1
340R6=79.36
350R7=530.5
360N3=360
370N4=410
379 REM CIRCUIT DATA
380R0=1E6
390R9=1E6
400C6=1E-12
410C7=1E-12
420V0=10.0
430G5=1
440F=10E3
450L2=.025
470L7=L3-2*(L4+L5)
480L8=L7+L4
490L9=L5+2*L6
499 REM CØNDUCTØR DATA
500 DIM K(3),N(3),L(5)
510 C(1)=.0266
520 C(2)=.028
530 C(3)=.0294
540 K1=5.393
545 U1=1
550 K2=3.632
555 U2=1
560 GØ SUB 600
590 GØ TØ 1000
599 REM SUBRØUTINE FØR M
600 W=2*P9*F
610 M1=0
620 IF K1>1E9 THEN 640
630 M1=.5094*U1*F*R5*R5/K1
640 M2=0
650 IF K2>1E9 THEN 670
660 M2=.5094*U2*F*R5*R5/K2
670 RETURN
999 REM PRINT CØIL DATA
1000 PRINT "R1=";R1,"R2=";R2,"DRIVER LENGTH IS";L3
1010 PRINT"R3=";R3,"R4=";R4,"PICK UP LENGTH IS";L4
1020 PRINT "CØIL MEAN RADIUS";R5;"INCHES      ØPERATING FREQUENCY";F
```

```
1030 PRINT "PICK UP RECESSED";L5
1040 PRINT "MIN LIFT-ØFF=";L6;"LIFT-ØFF INCREMENT=";L2
1050 PRINT "U1=";U1,"M1=";M1,"RESISTIVITY=";K1;"MICRØHM CM"
1060 PRINT "U2=";U2,"M2=";M2,"RESISTIVITY=";K2;"MICRØHM CM"
1070 PRINT "THICKNESS=",C(1),C(2),C(3)
1100 REM PRØGRAM BEGINS
1110 REM FØR INTEGRATIØNS
1120 GØ SUB 1500
1130 REM FØR INDUCTANCES AND CIRCUIT; MAGNITUDE AND PHASE
1140 GØ SUB 6000
1150 REM FØR DISCRIMINATØR VØLTAGE AND PHASE SHIFT
1160 GØ SUB 6500
1170 REM FØR PRINTING ØF RESULTS
1180 GØ SUB 6700
1190 REM FØR AV. PHASE SHIFT AND LIFT-ØFF ERRØR
1200 GØ SUB 7000
1400 REM FØR CØIL AND ATTENUATØR DESIGNS, AND DRIFT
1410 GØ TØ 7200
1499 REM SUBRØUTINE FØR INTEGRATIØN
1500 A3=0
1510 A4=0
1520 FØR I=1 TØ 3
1530 FØR J=1 TØ 5
1540 A(I,J)=0
1550 B(I,J)=0
1560 C(I,J)=0
1570 D(I,J)=0
1580 E(I,J)=0
1590 F(I,J)=0
1600 NEXT J
1610 NEXT I
1620 LET S2=5
1630 B1=0
1640 B2=5
1650 S1=1E-2
1660 FØR X=B1+S1/2 TØ B2 STEP S1
1670 GØ SUB 2000
1680 NEXT X
1690 B1=B2
1700 B2=B2+S2
1710 S1=.05
1720 IF X<9 THEN 1660
1730 S1=.1
1740 IF X<29 THEN 1660
1750 S1=.2
1760 IF X<39 THEN 1660
1770 S1=.5
1780 IF X<79 THEN 1660
1790 RETURN
1998 REM SUBRØUTINE FØR L-FACTØR AND INTEGRANTS
1999 REM FØR J-FACTØR
2000 GØ SUB 2700
2010 W5=0
2020 W2=0
2030 W6=0
2040 W7=0
2050 W4=1
2060 W8=1
```

```
2070 W3=1
2080 IF X*L5>20 THEN 2100
2090 W5=EXP(-X*L5)
2100 IF X*L2>20 THEN 2120
2110 W2=EXP(-X*L2)
2120 IF X*L6>20 THEN 2140
2130 W6=EXP(-X*L6)
2140 IF X*L7>20 THEN 2160
2150 W7=EXP(-X*L7)
2160 IF X*L4>15 THEN 2220
2170 W4=1-EXP(-X*L4)
2180 IF X*L8>15 THEN 2220
2190 W8=1-EXP(-X*L8)
2200 IF X*L3>15 THEN 2220
2210 W3=1-EXP(-X*L3)
2220 IF X>30 THEN 2460
2230 IF X*L9>20 THEN 2460
2240 A5=W6*W6*W3*W4*W5*W8*S3
2250 A6=W6*W6*W3*W3*S4
2260 A7=W6*W6*W4*W4*W5*W5*W8*W8*S5
2270 L(1)=1
2280 FØR J=2 TØ 5
2290 L(J)=0
2300 IF J*X*L2>20 THEN 2320
2310 L(J)=W2*L(J-1)
2320 NEXT J
2329 REM FØR GAMMA FACTØR
2330 GØ SUB 3200
2340 FØR I=1 TØ 3
2350 FØR J=1 TØ 5
2360 Q1=K(I)*L(J)*L(J)
2370 Q2=-N(I)*L(J)*L(J)
2380 A(I,J)=A(I,J)+Q2*A5
2390 B(I,J)=B(I,J)+Q1*A5
2400 C(I,J)=C(I,J)+Q2*A6
2410 D(I,J)=D(I,J)+Q1*A6
2420 E(I,J)=E(I,J)+Q2*A7
2430 F(I,J)=F(I,J)+Q1*A7
2440 NEXT J
2450 NEXT I
2460 A3=A3+2*(X*L3-W3)*S4
2470 A4=A4+(4*(X*L4-W4)-2*W7*W4*W4)*S5
2480 RETURN
2699 REM SUBRØUTINE FØR J5=J(R1,R2)/X↑3,J6=J(R3,R4)/X↑3
2700 R=R1
2710 GØ SUB 2900
2720 J1=Q2
2730 R=R2
2740 GØ SUB 2900
2750 J5=Q2-J1
2760 R=R3
2770 GØ SUB 2900
2780 J3=Q2
2790 R=R4
2800 GØ SUB 2900
2810 J6=Q2-J3
2820 S3=S1*J5*J6
```

```
2830 S4=S1*J5*J5
2840 S5=S1*J6*J6
2850 RETURN
2899 REM SUBRØUTINE FØR Q2=J(R,0)*X↑3
2900 Z=X*R
2910 IF Z>5 THEN 3000
2920 Q1=R*R*R/2
2930 Q2=Q1/3
2940 Q3=INT(2*Z)+3
2950 FØR Q=1 TØ Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 GØ TØ 3050
3000 Q1=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
3010 Q1=((Q1-0.1730503)/Z+0.7034845)/Z-0.064109E-3
3020 Q2=(((-5.817517/Z+2.105874)/Z-0.6896196)/Z+0.4952024)/Z
3030 Q2=(Q2-0.187344E-2)/Z+0.7979095
3040 Q2=(1-SQR(Z)*(Q2*CØS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3198 REM SUBRØUTINE FØR GAMMA FACTØR(K(I),N(I))
3199 REM BETE (X1,Y1) AND (X2,Y2)
3200 Q1=X*X
3210 Q2=Q1*Q1
3220 X1=X/U1
3230 Y1=0
3240 IF M1=0 THEN 3280
3250 Q3=SQR(Q2+M1*M1)
3260 X1=.707106781*SQR(Q3+Q1)/U1
3270 Y1=.707106781*SQR(Q3-Q1)/U1
3280 X2=X/U2
3290 Y2=0
3300 IF M2=0 THEN 3340
3310 Q3=SQR(Q2+M2*M2)
3320 X2=.707106781*SQR(Q3+Q1)/U2
3330 Y2=.707106781*SQR(Q3-Q1)/U2
3339 REM FØR GAMMA FACTØR
3340 Q1=X2+X1
3350 Q2=X2-X1
3360 Q3=Y2+Y1
3370 Q4=Y2-Y1
3380 Q5=X+X2
3390 Q6=X-X2
3400 T1=Q5*Q2-Y2*Q4
3410 T2=Q5*Q4+Y2*Q2
3420 T3=Q6*Q2+Y2*Q4
3430 T4=Q6*Q4-Y2*Q2
3440 T5=Q6*Q1+Y2*Q3
3450 T6=Q6*Q3-Y2*Q1
3460 T7=Q5*Q1-Y2*Q3
3470 T8=Q5*Q3+Y2*Q1
3480 FØR I=1 TØ 3
3490 C0=2*C(I)/R5*U2
3500 IF X2*X0>30 THEN 3590
3510 Q7=EXP(X2*C0)
3520 Q8=Q7*CØS(Y2*C0)
3530 Q9=Q7*SIN(Y2*C0)
3540 V3=T1+T5*Q8-T6*Q9
```

```
3550 V4=T2+T5*Q9+T6*Q8
3560 V7=T3+T7*Q8-T8*Q9
3570 V8=T4+T7*Q9+T8*Q8
3580 GØ TØ 3630
3590 V3=Q6
3600 V4=-Y2
3610 V7=Q5
3620 V8=Y2
3630 V9=V7/V8+V8/V7
3640 K(I)=(V3/V8+V4/V7)/V9
3650 N(I)=(V4/V8-V3/V7)/V9
3660 NEXT I
3670 RETURN
5999 REM SUBRØUTINE FØR CIRCUIT, MAGNITUDE, AND PHASE
6000N1=N3/((R2-R1)*L3)
6010N2=N4/((R4-R3)*L4)
6020Q0=6.300475204E-7*F*R5
6030 W1=W*C6*R0
6040 W2=W*C7*R9
6050 W3=1-W1*W2
6060 W4=W1+W2
6070 FØR I=1 TØ 3
6080 FØR J=1 TØ 5
6090Z8=Q0*N1*N2*A(I,J)
6100Z9=Q0*N1*N2*B(I,J)
6110Z=Q0*N1*N1*C(I,J)
6120Z2=Q0*N1*N1*(D(I,J)+A3)
6130Z1=Q0*N2*N2*E(I,J)
6140Z3=Q0*N2*N2*(F(I,J)+A4)
6150 Q1=R0+R6+Z-W1*Z2
6160 Q2=R9+R7+Z1-W2*Z3
6170 Q3=Z2+W1*(R6+Z)
6180 Q4=Z3+W2*(R7+Z1)
6190 Q5=Z8*Z8-Z9*Z9
6200 Q6=2*Z8*Z9
6210 Q7=Q1*Q2-Q3*Q4-(W3*Q5-W4*Q6)
6220 Q8=Q1*Q4+Q3*Q2-(W4*Q5+W3*Q6)
6230 Q9=Z8*Q7+Z9*Q8
6240 W5=Z9*Q7-Z8*Q8
6250 M(I,J)=G5*R9*V0*SQR(Q9*Q9+W5*W5)/(Q7*Q7+Q8*Q8)
6260 P(I,J)=ATN(W5/Q9)
6270 IF Q9>0 THEN 6290
6280 P(I,J)=P(I,J)+SGN(W5)*P9
6290 NEXT J
6300 NEXT I
6310 RETURN
6499 REM SUBRØUTINE FØR DISC. VØLTAGE AN PHASE SHIFT
6500 Q1=M(2,5)*SIN(P(2,5))-M(2,1)*SIN(P(2,1))
6510 Q2=-M(2,5)*CØS(P(2,5))+M(2,1)*CØS(P(2,1))
6520 Q3=ATN(Q1/Q2)
6530 IF Q2>0 THEN 6550
6540 Q3=Q3+SGN(Q1)*P9
6550 V1=M(2,1)*SIN(Q3+P(2,1))
6555 Ø1=Q3
6556 Ø2=V1
6560 FØR I=1 TØ 3
6570 FØR J=1 TØ 5
```

```
6580 Q(I,J)=Q3-ATN(V1/SQR(M(I,J)*M(I,J)-V1*V1))+P(I,J)
6590 NEXT J
6600 NEXT I
6610 RETURN
6699 REM SUBRØUTINE FØR PRINTING RESULTS
6700PRINT"DRIVER RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6710PRINTR6,Q0*N1*N1*A3/W,N3,C6,(D(2,3)+A3)/A3
6720PRINT"PICKUP RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6730PRINTR7,Q0*N2*N2*A4/W,N4,C7,(F(2,3)+A4)/A4
6740PRINT "DRIVING VØLT","SERIES RES","AMP GAIN","INPUT IMP"
6750PRINTV0,R0,G5,R9
6760PRINT "DISCRIMINATØR VØLTAGE IS";V1
6770 PRINT
6780 PRINT L6,L6+L2,L6+2*L2,L6+3*L2,L6+4*L2
6790 FØR I=1 TØ 3
6800 PRINT
6810 PRINT M(I,1),M(I,2),M(I,3),M(I,4),M(I,5)
6820 PRINT P(I,1),P(I,2),P(I,3),P(I,4),P(I,5)
6830 PRINT Q(I,1),Q(I,2),Q(I,3),Q(I,4),Q(I,5)
6840 NEXT I
6850 RETURN
6999 REM SUBRØUTINE FØR AV. PHASE SHIFT AND LIFT-ØFF ERRØR
7000 Q1=Q(1,1)
7010 Q2=Q(1,1)
7020 FØR J=2 TØ 5
7030 IF Q(1,J)<Q1 THEN 7050
7040 Q1=Q(1,J)
7050 IF Q(1,J)>Q2 THEN 7070
7060 Q2=Q(1,J)
7070 NEXT J
7080 Q=(Q(1,1)+Q(1,2)+Q(1,3)+Q(1,4)+Q(1,5))/5
7090 Q=Q-(Q(3,1)+Q(3,2)+Q(3,3)+Q(3,4)+Q(3,5))/5
7092 Ø=Q
7100 PRINT"PHASE SHIFT";Q;"LIFT-ØFF";Q1-Q2;"IN %";100*(Q1-Q2)/Q
7110 PRINT"IN DEGREE";Q*P8,(Q1-Q2)*P8
7120 RETURN
7199 REM FØR CØIL DESIGN, ATTENUATØR, DRIFT, AND EXIT
7200PRINT"1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL"
7210INPUT N5
7220PRINT
7230ØN N5 GØ TØ 7300,8200,8600,9900
7299 REM FØR CØIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FØR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 GØ SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER";N3;"TURNS ØF #";G;"WIRE";
7390 PRINT Q7;"/LAYER";Q8;"LAYERS";R6;"ØHM"
7399 REM FØR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
7430 W2=R4
```

```
7440 W3=L4
7450 GØ SUB 7510
7460 N4=Q2
7470 R7=2*Q9
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIRE";
7490 PRINT Q7;"/LAYER";Q8;"LAYERS";R7;"ØHMS TØTAL"
7500 GØ TØ 1140
7509 REM SUBRØUTINE FØR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FØR GAGE
7540 G=Q1
7550 IF G>.5 THEN 7640
7560 Q5=.95*SQR((W2-W1)*W3/Q2)
7570 Q6=1.0371E-5/Q5/Q5
7580 G0=40
7590 G=40+10*(LØG(Q6)-LØG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 GØ TØ 7590
7630 G=INT(G)
7639 REM FØR TURN NUMBER AND R6
7640 Q6=(.9989+.017*(G/10-1))*10↑(G/10-4)
7650 Q5=SQR(1.0371E-5/Q6)
7660 IF G> 40 THEN 7690
7670 Q5=(.460655*LØG(Q5*1E3)-.43444)*1E-3+Q5
7680 GØ TØ 7700
7690 Q5=(98.02228*Q5+2.56791E-2)*1E-3+Q5
7700 Q7=INT(W3/Q5)
7710 Q8=INT((W2-W1)/Q5)
7720 IF Q2>.5 THEN 7740
7730 Q2=Q7*Q8
7740 Q9=Q2*Q6*(W2+W1)*P9/12
7750 RETURN
8199 REM FØR ATTENUATØR DESIGN
8200 PRINT "DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP"
8210 INPUT Q1,Q2,Q3,Q4
8220 IF Q1=0 THEN 8240
8230 R0=Q1
8240 IF Q2=0 THEN 8260
8250 C6=Q2
8260 IF Q3=0 THEN 8280
8270 R9=Q3
8280 IF Q4=0 THEN 8300
8290 C7=Q4
8300 Q1=Q0*N1*N1*(D(2,3)+A3)/W
8310 Q2=Q0*N2*N2*(F(2,3)+A4)/W
8320 PRINT "DVR CT";1/(W*SQR(Q1*C6));"BELØW RES";
8330 PRINT SQR(Q1/C6);"ØPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELØW RES";
8350 PRINT SQR(Q2/C7);"ØPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 GØ TØ 1140
8599 REM FØR DRIFTS
8600 PRINT"SYSTEM DRIFT VARIATIØNS"
8610 E1=.01
8620 E2=.01
8630 E3=.01
```

```
8640 E4=.01
8650 E7=.01
8660 E8=.01
8670 E9=.01
8680 A1=.01
8690 A2=.01
8700 A8=.01
8705 A9=.01
8710 PRINT "% VARIATN","PARAMETER","RADIAN","DEGREE","% ØF RANGE"
8720 IF E1=0 THEN 8770
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 GØ SUB 9320
8760 R6=R6/(1+E1)
8770 IF E2=0 THEN 8820
8780 R7=R7*(1+E2)
8790 PRINT 100*E2,"PICKUP RES",
8800 GØ SUB 9320
8810 R7=R7/(1+E2)
8820 IF E3=0 THEN 8870
8830 C6=C6*(1+E3)
8840 PRINT 100*E3,"DVR SHUNT CAP",
8850 GØ SUB 9320
8860 C6=C6/(1+E3)
8870 IF E4=0 THEN 8920
8880 C7=C7*(1+E4)
8890 PRINT 100*E4,"P-U SHUNT CAP",
8900 GØ SUB 9320
8910 C7=C7/(1+E4)
8920 IF E7=0 THEN 8970
8930 R0=R0*(1+E7)
8940 PRINT 100*E7,"SERIES RES",
8950 GØ SUB 9320
8960 R0=R0/(1+E7)
8970 IF E8=0 THEN 9020
8980 R9=R9*(1+E8)
8990 PRINT 100*E8,"AMP INPUT RES",
9000 GØ SUB 9320
9010 R9=R9/(1+E8)
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VØLT",
9050 GØ SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 GØ SUB 9300
9110 F=F/(1+A1)
9120 IF A2=0 THEN 9170
9130 R5=R5*(1+A2)
9140 PRINT 100*A2,"MEAN RADIUS",
9150 GØ SUB 9300
9160 R5=R5/(1+A2)
9170 IF A8=0 THEN 9220
9180 K1=K1*(1+A8)
9190 PRINT 100*A8,"BASE RESISTVY",
```

```
9200 GØ SUB 9300
9210 K1=K1/(1+A8)
9220 IF A9=0 THEN 9270
9230 K2=K2*(1+A9)
9240 PRINT 100*A9,"CLADDING RES",
9250 GØ SUB 9300
9260 K2=K2/(1+A9)
9270 GØ TØ 7200
9299 REM SUBRØUTINE FØR DRIFT
9300 GØ SUB 600
9310 GØ SUB 1500
9320 GØ SUB 6000
9330 O1=0
9340 FØR I=1 TØ3
9350 FØR J=1 TØ 5
9360 O2=Ø1-ATN(Ø2/SQR(M(I,J)*M(I,J)-Ø2*Ø2))+P(I,J)-Q(I,J)
9370 IF ABS(O1)>ABS(O2) THEN 9390
9380 Ø1=O2
9390 NEXT J
9400 NEXT I
9410 PRINT O1,180*O1/P9,100*O1/Ø
9420 RETURN
9900 END
```

RFCLAD, FORTRAN Version

The FORTRAN version of RFCLAD is very similar to the BASIC version. The line numbers given are only for identification and editing purposes and have no effect on the actual execution of the FORTRAN program. The input data for the program is contained in lines 250 through 520. The data must be typed in the seventh column, or six spaces must first be typed. The data are inputed as follows:

00250	R5 = (coil mean radius in inches)
00260	R1 = (normalized inner radius of driver coil)
00270	R2 = (normalized outer radius of driver coil)
00280	L3 = (normalized length of driver coil)
00290	R3 = (normalized inner radius of pickup coil)
00300	R4 = (normalized outer radius of pickup coil)
00310	L4 = (normalized length of pickup coil)
00320	L5 = (normalized length of recess of each pickup coil from the face of the driver coil)
00330	L6 = (normalized minimum lift-off of the driver coil)
00340	R6 = (resistance of driver coil in ohms)
00350	R7 = (resistance of both pickup coils in ohms)
00360	N3 = (number of turns on the driver coil)
00370	N4 = (number of turns on each pickup coil)
00380	R0 = (driver amplifier series resistance in ohms)
00390	R9 = (pickup amplifier shunt resistance in ohms)
00400	C6 = (shunt capacitance of driver circuit in farads)
00410	C7 = (shunt capacitance of pickup circuit in farads)
00420	V0 = (output voltage in volts)
00430	GAIN = (amplifier gain)
00440	FREQ = (operating frequency in Hertz)
00450	L2 = (normalized lift-off increment of the driver coil)
00460	RH01 = (resistivity of base material in microhm-cm)
00470	U1 = (relative magnetic permeability of base material)
00480	RH02 = (resistivity of cladding material in microhm-cm)
00490	U2 = (relative magnetic permeability of cladding material)

00500 CLAD(1) = (numerical value of minimum cladding thickness in inches)

00510 CLAD(2) = (numerical value of nominal cladding thickness in inches)

00520 CLAD(3) = (numerical value of maximum cladding thickness in inches)

The print-out of the FORTRAN version of RFCLAD is practically identical to the BASIC version and will not be repeated. The main difference is that the question mark is not printed out when the program is ready to accept data. The Coil Design, Attenuator Design, Drift Check, and Continue Calculations options are the same. The line numbers, constant names, and parameter varied in the drift calculations are as follows:

Line Number	Constant	Parameter Varied
03270	DR1	Driver Resistance
03280	DR2	Pickup Resistance
03290	DR3	Driver Shunt Capacitance
03300	DR4	Pickup Shunt Capacitance
03310	DR5	Series Resistance
03320	DR6	Amplifier Input Resistance
03330	DR7	Applied Voltage
03340	DR8	Frequency
03350	DR9	Mean Radius
03360	DR10	Base Resistivity
03370	DR11	Cladding Resistivity

For example, to vary the driver resistance by 2% one would type:

03270 DR1 = 0.02

As in the BASIC version, the last four drifts require that the entire numerical integration be repeated and are relatively long running. If any of the drifts is set equal to zero, it will be omitted from the drift calculations.

Sample Calculation of RFCLAD.F4

Let us suppose that we wish to design a reflection type coil, identical to the one designed by the BASIC version. We will put the following data in the program (generally by using the EDIT RFCLAD.F4 command on the PDP-10 and inserting the statements). All coil and lift-off dimensions are normalized by dividing by the coil mean radius, except the coil mean radius, which is in inches.

```
R5 = .08325
R1 = .75
R2 = 1.25
L3 = .36
R3 = .36
R4 = .696
L4 = .096
L5 = 0.0
L6 = .1
R6 = 79.36
R7 = 530.5
N3 = 360.
N4 = 410.
R0 = 1.E6
R9 = 1.E6
C6 = 1.E-12
C7 = 1.E-12
V0 = 10.
GAIN = 1
FREQ = 1.0E4
L2 = .025
RHO1 = 5.39261
U1 = 1.
RHO2 = 3.63204
U2 = 1.
```

```
500       CLAD(1) = .0266
510       CLAD(2) = .028
520       CLAD(3) = .0294
```

The FORTRAN program may now be executed. The print-out will be essentially identical to the BASIC print-out and will not be repeated. The FORTRAN version of RFCLAD follows.

```
C IN THIS PROGRAM, THE BASE RESISTIVITY IS RHØ1 AND
C   THE CLADDING RESISTIVITY IS RHØ2
C SIGMA IS THE GAMMA FACTØR
      CØMPLEX BETA1,BETA2,EX1,RNUM,DEN,SIGMA
      CØMPLEX TMUT,DRIVER,PICKUP
      REAL L3,L4,L5,L6,L2,N3,N4,K1,K2
      CØMMØN X,Z,Q1,PI/B1/R1,R2,R3,R4,L3,L4,R0,R6,R7
      CØMMØN /B1/R9,C6,C7,V0,GAIN,W,FREQ,R5,N3,N4
      CØMMØN /B2/TMUT,DRIVER,PICKUP,AIR1,AIR2/B4/GAGE,XIN
      CØMMØN /B3/XØUT,XLEN,TURNS,N1A,J1,PERLAY,XLAY
      DIMENSIØN CLAD(3),RL(5),SIGMA(3),TMUT(3,5),DRIVER(3,5)
      DIMENSIØN PICKUP(3,5),TMAG(3,5),PHASE(3,5),SHIFT(3,5)
      EQUIVALENCE (RHØ1,K1),(RHØ2,K2),(GAIN,G5),(FREQ,F)
      PI=3.14159265
      RAD=180.0/PI
C
C
C
C
C
C
      JKL=0
C THE FØLLØWING ARE INPUT DATA FØR THE PARAMETERS ØF
C   THE CØILS,MATERIAL, AND CIRCUIT
      R5=.08325
      R1=.75
      R2=1.25
      L3=.36
      R3=.36
      R4=.696
      L4=.096
      L5=0.0
      L6=.1
      R6=79.36
      R7=530.5
      N3=360.0
      N4=410.0
      R0=1.0E6
      R9=1.0E6
      C6=1.0E-12
      C7=1.0E-12
      V0=10.0
      GAIN=1.0
      FREQ=1.0E4
      L2=0.025
      RHØ1=5.393
      U1=1.0
      RHØ2=3.632
      U2=1.0
      CLAD(1)=0.0266
      CLAD(2)=0.028
      CLAD(3)=0.0294
    5 W=2.0*PI*FREQ
      IF(RHØ1.GT.1.0E9) GØ TØ 10
      RM1=0.5094*U1*FREQ*R5*R5/RHØ1
      GØ TØ 20
   10 RM1=0.0
```

```
   20 RM2=0.5094*U2*FREQ*R5*R5/RHØ2
C THE SYSTEM PARAMETERS ARE PRINTED ØUT
      IF(JKL.NE.O) GØ TØ 105
      TYPE 30,R1,R2,L3
   30 FØRMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
     1F8.5)
      TYPE 40,R3,R4,L4
   40 FØRMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
     1F8.5)
      TYPE 50,R5,FREQ
   50 FØRMAT(1H ,17HCØIL MEAN RADIUS=,F8.5,7H INCHES,3X,
     120HØPERATING FREQUENCY=,1PE12.5)
      TYPE 60,L5
   60 FØRMAT(1H ,15HPICKUP RECESSED,F8.5)
      TYPE 70,L6,L2
   70 FØRMAT(1H ,13HMIN LIFT-ØFF=,F8.5,3X,19HLIFT-ØFF INCREMENT=,
     1F8.5)
      TYPE 80,U1,RM1,RHØ1
   80 FØRMAT(1H ,3HU1=,F6.2,5X,3HM1=,F9.5,2X,12HRESISTIVITY=,
     11PE12.5,11H MICRØHM CM)
      TYPE 90,U2,RM2,RHØ2
   90 FØRMAT(1H ,3HU2=,F6.2,5X,3HM2=,F9.5,2X,12HRESISTIVITY=,
     11PE12.5,11H MICRØHM CM)
      TYPE 100,CLAD(1),CLAD(2),CLAD(3)
  100 FØRMAT(1H ,10HTHICKNESS=,F8.5,2(8X,F8.5))
C THE INTEGRATIØN IS PERFØRMED BY THE TRAPEZØIDAL METHØD,
C   EVALUATING AT THE CENTER ØF THE INTERVAL; FØR X LARGE
C   THE INTEGRAL CØNVERGES RAPIDLY,SØ LARGER INTERVALS
C   ARE TAKEN
C IN THE INTEGRATIØN TMUT, DRIVER, PICKUP, AIR1, AND
C   AIR2 ARE CALCULATED
  105 S1=0.01
      S2=5.0
      B1=0.0
      B2=S2
      AIR1=0.0
      AIR2=0.0
      DØ 108 J=1,3
      DØ 108 K=1,5
      DRIVER(J,K)=(0.0,0.0)
      PICKUP(J,K)=(0.0,0.0)
      TMUT(J,K)=(0.0,0.0)
  108 CØNTINUE
  110 I1=(B2-B1)/S1
      X=B1-S1/2.0
      DØ 170 I=1,I1
      X=X+S1
      Z=R2*X
      Q1=R2
C SUBRØUTINE BESSEL EVALUATES THE INTEGRAL ØF
C   THE PRØDUCT ØF THE BESSEL FUNCTIØN AND ITS
C   ARGUMENT
      CALL BESSEL(VAL2)
      Z=R1*X
      Q1=R1
      CALL BESSEL(VAL1)
```

```
      Z=R4*X
      Q1=R4
      CALL BESSEL(VAL4)
      Z=R3*X
      Q1=R3
      CALL BESSEL(VAL3)
      S3=S1*(VAL4-VAL3)*(VAL2-VAL1)
      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
      EX3=EXP(-X*L3)
      W1=1.0-EX3
      EX4=EXP(-X*L4)
      W2=1.0-EX4
      EX5=EXP(-X*L5)
      W3=EX3/(EX4*EX4*EX5*EX5)
      IF(X.GT.30.0) GØ TØ 160
C FRØM HERE THRØUGH LINE 130,SIGMA IS CALCULATED
      BETA2=CSQRT(CMPLX(X*X,RM2))/U2
      DØ 130 J=1,3
      IF(REAL(CLAD(J)/R5*BETA2*U2).GT.15.0) GØ TØ 120
      EX1=CEXP(2.0*CLAD(J)/R5*BETA2*U2)
      BETA1=CSQRT(CMPLX(X*X,RM1))/U1
      RNUM=(X+BETA2)*(BETA2-BETA1)+(X-BETA2)*(BETA2+BETA1)*EX1
      DEN=(X-BETA2)*(BETA2-BETA1)+(X+BETA2)*(BETA2+BETA1)*EX1
      SIGMA(J)=RNUM/DEN
      GØ TØ 130
  120 SIGMA(J)=(X-BETA2)/(X+BETA2)
  130 CØNTINUE
      EX2=EXP(-2.0*X*L2)
      EX6=EXP(-2.0*X*L6)
      W4=1.0-EX4*W3
      W5=EX5*EX6*W1*W2*W4
      W6=EX6*W1*W1
      W7=W2*W2*EX6*EX5*EX5*W4*W4
      RL(1)=1.0
      DØ 140 K=2,5
  140 RL(K)=EX2*RL(K-1)
      DØ 150 K=1,3
      DØ 150 L=1,5
      TMUT(K,L)=TMUT(K,L)+S3*W5*RL(L)*SIGMA(K)
      DRIVER(K,L)=DRIVER(K,L)+S4*W6*RL(L)*SIGMA(K)
  150 PICKUP(K,L)=PICKUP(K,L)+S5*W7*RL(L)*SIGMA(K)
  160 AIR1=AIR1+S4*2.0*(X*L3-W1)
      AIR2=AIR2+S5*(4.0*(X*L4-W2)-2.0*W2*W2*W3)
  170 CØNTINUE
      B1=B2
      B2=B2+S2
      S1=0.05
      IF(X.LT.9.0) GØ TØ 110
      S1=0.1
      IF(X.LT.29.0) GØ TØ 110
      S1=0.2
      IF(X.LT.39.0) GØ TØ 110
      S1=0.5
      IF(X.LT.79.0) GØ TØ 110
C THE INTEGRATIØN ENDS HERE
      IF(JKL.NE.0) GØ TØ 552
C NEXT THE PRØPERTIES ØF THE CØILS ARE DETERMINED AND PRINTED
```

```
180 CALL CIRCT(TMAG,PHASE,QO,T1,T2)
    CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
    TYPE 190
190 FØRMAT(1H ,10HDRIVER RES,4X,10HINDUCTANCE,4X,8HNØ TURNS,
   16X,9HSHUNT CAP,5X,9HNØR IM PT)
    Q1=QO*T1*T1*AIR1/W
    Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
    Q3=QO*T2*T2*AIR2/W
    Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
    TYPE 200,R6,Q1,N3,C6,Q2
200 FØRMAT(1H ,1PE12.5,2X,1PE12.5,2X,0PF8.1,6X,1PE12.5,2X,
   10PF9.6)
    TYPE 210
210 FØRMAT(1H ,10HPICKUP RES,4X,10HINDUCTANCE,4X,8HNØ TURNS,
   16X,9HSHUNT CAP,5X,9HNØR IM PT)
    TYPE 200,R7,Q3,N4,C7,Q4
    TYPE 220
220 FØRMAT(1H ,12HDRIVING VØLT,2X,10HSERIES RES,4X,
   18HAMP GAIN,6X,9HINPUT IMP)
    TYPE 230,VO,RO,GAIN,R9
230 FØRMAT(1H ,F5.1,9X,1PE12.5,2X,0PF8.1,6X,1PE12.5)
    TYPE 240,V1
240 FØRMAT(1H ,22HDISCRIMINATØR VØLTAGE=,1PE12.5)
    TYPE 250
250 FØRMAT(1H )
    RL(1)=L6
    DØ 260 I=2,5
260 RL(I)=L2+RL(I-1)
    TYPE 270,RL
270 FØRMAT(1H ,4(F6.3,8X),F6.3)
    TYPE 250
C THE VØLTAGE MAGNITUDE,PHASE,AND SHIFT ARE PRINTED FØR
C   THE VARIØUS LIFT-ØFF VALUES
    DØ 280 I=1,3
    TYPE 290,(TMAG(I,J),J=1,5)
    TYPE 290,(PHASE(I,J),J=1,5)
    TYPE 290,(SHIFT(I,J),J=1,5)
    TYPE 250
280 CØNTINUE
290 FØRMAT(1H ,4(1PE12.5,2X),1PE12.5)
    CALL SENS(SHIFT,RAD,SEN)
C THE USER SELECTS ØNE ØF FØUR PØSSIBILITIES
295 TYPE 300
300 FØRMAT(' 1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK
   1  4 CØN CAL')
    TYPE 250
    ACCEPT 310,N5
310 FØRMAT(I1)
    GØ TØ(320,450,540,690),N5
C THE FIRST PØSSIBILITY PRINTS FACTØRS IN THE  CØIL
C   DESIGN; USER INPUTS INTEGER DATA AS REQUESTED
320 TYPE 330
330 FØRMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
   1 TURNS')
    TYPE 250
    ACCEPT 340,N1A,N2A,N3A,N4A
340 FØRMAT(4I)
    IF (N1A*N2A.EQ.0) GØ TØ 350
```

```
      GAGE=N1A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      TURNS=N2A
      N3=N2A
      N1A=-1
      J1=1
      CALL GAGER(R6)
      GØ TØ 370
  350 IF(N1A.EQ.0) GØ TØ 360
      GAGE=N1A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=1
      CALL GAGER(R6)
      N3=TURNS
      GØ TØ 370
  360 IF(N2A.EQ.0) GØ TØ 390
      N3=N2A
      TURNS=N2A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=0
      CALL GAGER(R6)
  370 TYPE 380,TURNS,GAGE,PERLAY,XLAY,R6
  380 FØRMAT(1H ,6HDRIVER,F6.1,10H TURNS ØF#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  390 IF(N3A*N4A.EQ.0) GØ TØ 400
      GAGE=N3A
      TURNS=N4A
      N4=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      R7=2.0*R7
      GØ TØ 420
  400 IF(N3A.EQ.0) GØ TØ 410
      GAGE=N3A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      N4=TURNS
      R7=2.0*R7
      GØ TØ 420
  410 IF(N4A.EQ.0) GØ TØ 440
      N4=N4A
      TURNS=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=0
```

```
      CALL GAGER(R7)
      R7=2.0*R7
  420 TYPE 430,TURNS,GAGE,PERLAY,XLAY,R7
  430 FØRMAT(1H ,6HPICKUP,F6.1,10H TURNS EA#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  440 GØ TØ 180
C THE SECØND PØSSIBILITY DEALS WITH ATTENUATØR DESIGN;
C   USER INPUTS REQUESTED DATA IN E FIELD TYPE
  450 TYPE 460
  460 FØRMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
     1 SHUNT CAP')
      TYPE 250
      ACCEPT 470,P1,P2,P3,P4
  470 FØRMAT(4E)
      IF(P1.EQ.0.0) GØ TØ 480
      R0=P1
  480 IF(P2.EQ.0.0) GØ TØ 490
      C6=P2
  490 IF(P3.EQ.0.0) GØ TØ 500
      R9=P3
  500 IF(P4.EQ.0.0) GØ TØ 510
      C7=P4
  510 Q5=1.0/(W*SQRT(Q1*Q2*C6))
      Q6=SQRT(Q1*Q2/C6)
      Q7=R0/(W*Q1*Q2)
      Q8=1.0/(W*SQRT(Q3*Q4*C7))
      Q9=SQRT(Q3*Q4/C7)
      Q10=R9/(W*Q3*Q4)
      TYPE 520,Q5,Q6,Q7
  520 FØRMAT(1H ,7HDVR CKT,1PE12.5,10H BELØW RES,1PE12.5,
     18H ØPT RES,1PE12.5,11H RES/REACT.)
      TYPE 530,Q8,Q9,Q10
  530 FØRMAT(1H ,7HP-U CKT,1PE12.5,10H BELøw RES,1PE12.5,
     18H ØPT RES,1PE12.5,11H RES/REACT.)
      GØ TØ 180
C THE THIRD PØSSIBILITY EXAMINES THE EFFECTS ØF DRIFT
C   ØN THE SYSTEM
  540 TYPE 550
  550 FØRMAT(1H ,23HSYSTEM DRIFT VARIATIØNS)
      DR1=0.01
      DR2=0.01
      DR3=0.01
      DR4=0.01
      DR5=0.01
      DR6=0.01
      DR7=0.01
      DR8=0.01
      DR9=0.01
      DR10=0.01
      DR11=0.01
      GØ TØ 559
  552 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      GØ TØ (675,678,681,684),JKL
  559 TYPE 560
  560 FØRMAT(1H ,11H% VARIATIØN,3X,13HPARAMETER VAR,1X,
     17HRADIANS,7X,7HDEGREES,7X,10H% ØF RANGE)
      IF(DR1.EQ.0.0) GØ TØ 580
```

```
      R6=R6*(1.0+DR1)
      DR100=100.0*DR1
      TYPE 570,DR100
  570 FØRMAT(1H ,F4.1,10X,13HDRIVER RES    $)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R6=R6/(1.0+DR1)
  580 IF(DR2.EQ.0.0) GØ TØ 600
      R7=R7*(1.0+DR2)
      DR100=100.0*DR2
      TYPE 590,DR100
  590 FØRMAT(1H ,F4.1,10X,13HPICKUP RES    $)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R7=R7/(1.0+DR2)
  600 IF(DR3.EQ.0.0) GØ TØ 620
      C6=C6*(1.0+DR3)
      DR100=100.0*DR3
      TYPE 610,DR100
  610 FØRMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      C6=C6/(1.0+DR3)
  620 IF(DR4.EQ.0.0) GØ TØ 640
      C7=C7*(1.0+DR4)
      DR100=100.0*DR4
      TYPE 630,DR100
  630 FØRMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      C7=C7/(1.0+DR4)
  640 IF(DR5.EQ.0.0) GØ TØ 660
      R0=R0*(1.0+DR5)
      DR100=100.0*DR5
      TYPE 650,DR100
  650 FØRMAT(1H ,F4.1,10X,13HSERIES RES    $)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R0=R0/(1.0+DR5)
  660 IF(DR6.EQ.0.0) GØ TØ 671
      R9=R9*(1.0+DR6)
      DR100=100.0*DR6
      TYPE 670,DR100
  670 FØRMAT(1H ,F4.1,10X,13HAMP INPUT RES$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R9=R9/(1.0+DR6)
  671 IF(DR7.EQ.0.0) GØ TØ 673
      V0=V0*(1.0+DR7)
      DR100=100.0*DR7
      TYPE 672,DR100
  672 FØRMAT(1H ,F4.1,10X,13HAPPLIED VØLT.$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      V0=V0/(1.0+DR7)
  673 IF(DR8.EQ.0.0) GØ TØ 676
      FREQ=FREQ*(1.0+DR8)
      DR100=100.0*DR8
      TYPE 674,DR100
  674 FØRMAT(1H ,F4.1,10X,13HFREQUENCY     $)
      JKL=1
      GØ TØ 5
  675 FREQ=FREQ/(1.0+DR8)
      JKL=0
  676 IF(DR9.EQ.0.0) GØ TØ 679
```

```
      R5=R5*(1.0+DR9)
      DR100=100.0*DR9
      TYPE 677,DR100
  677 FØRMAT(1H ,F4.1,10X,13HMEAN RADIUS  $)
      JKL=2
      GØ TØ 5
  678 R5=R5/(1.0+DR9)
      JKL=0
  679 IF(DR10.EQ.0.0) GØ TØ 682
      RHØ1=RHØ1*(1.0+DR10)
      DR100=100.0*DR10
      TYPE 680,DR100
  680 FØRMAT(1H ,F4.1,10X,13HBASE RESISTVY$)
      JKL=3
      GØ TØ 5
  681 RHØ1=RHØ1/(1.0+DR10)
      JKL=0
  682 IF(DR11.EQ.0.0) GØ TØ 295
      RHØ2=RHØ2*(1.0+DR11)
      DR100=100.0*DR11
      TYPE 683,DR100
  683 FØRMAT(1H ,F4.1,10X,13HCLADDING RES $)
      JKL=4
      GØ TØ 5
  684 RHØ2=RHØ2/(1.0+DR11)
      JKL=0
      GØ TØ 295
C THE FØURTH PØSSIBILITY ENDS CALCULATIØNS
  690 CALL EXIT
      END
      SUBRØUTINE BESSEL(VAL)
      CØMMØN X,Z,Q1,PI
      IF(Z.GT.5.0) GØ TØ 1010
      K=2.0*Z
      L=K+3
      F1=0.5*Q1*Q1*Q1
      VAL=F1/3.0
      DØ 1000 I=1,L
      AI=I
      F1=-F1*0.25*Z*Z/(AI*AI+AI)
      VAL=VAL+F1/(2.0*AI+3.0)
 1000 CØNTINUE
      GØ TØ 1020
 1010 X0=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
      X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
      X1=(((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
      X1=(X1-0.187344E-2)/Z+0.7979095
      VAL=(1.0-SQRT(Z)*(X1*CØS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
     1(X*X*X)
 1020 RETURN
      END
      SUBRØUTINE PHASET(A,B,C,V1,Ø3)
      DIMENSIØN A(3,5),B(3,5),C(3,5)
      Ø1=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
      Ø2=-(A(2,5)*CØS(B(2,5))-A(2,1)*CØS(B(2,1)))
      Ø3=ATAN2(Ø1,Ø2)
      V1=A(2,1)*SIN(Ø3+B(2,1))
      DØ 2000 I=1,3
```

```
      DØ 2000 J=1,5
 2000 C(I,J)=Ø3-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(I,J)
      RETURN
      END
      SUBRØUTINE SENS(Ø,RAD,Ø1)
      DIMENSIØN Ø(3,5)
      Ø9=Ø(1,1)
      ØO=Ø(1,1)
      DØ 3010 I=2,5
      IF(Ø(1,I).LT.Ø9) GØ TØ 3000
      Ø9=Ø(1,I)
 3000 IF(Ø(1,I).GT.ØO) GØ TØ 3010
      ØO=Ø(1,I)
 3010 CØNTINUE
      Ø1=(Ø(1,1)+Ø(1,2)+Ø(1,3)+Ø(1,4)+Ø(1,5))/5.0
      Ø1=Ø1-(Ø(3,1)+Ø(3,2)+Ø(3,3)+Ø(3,4)+Ø(3,5))/5.0
      XLØ=Ø9-ØO
      PERCT=100*XLØ/Ø1
      DEGR1=Ø1*RAD
      DEGR2=XLØ*RAD
      TYPE 3020,Ø1,XLØ,PERCT
 3020 FØRMAT(1H ,12HPHASE SHIFT=,1PE12.5,2X,8HLIFTØFF=,
     11PE12.5,2X,2H%=,1PE12.5)
      TYPE 3030,DEGR1,DEGR2
 3030 FØRMAT(1H ,7HDEGREE:,1PE13.5,5X,1PE13.5)
      RETURN
      END
      SUBRØUTINE GAGER(RES)
      CØMMØN /B3/G,D1,D2,RLN,T5,N1,J1,D,E
      PI=3.1415926536
      IF(J1.EQ.1) GØ TØ 4015
      N1=-1
      D3=0.95*SQRT((D2-D1)*RLN/T5)
      X2=1.0371E-5/(D3*D3)
      Q=40.0
 4000 G=40.0+10.0*(ALØG(X2)-ALØG(.9989+.017*(Q/10.0-1.0)))/2.3
     10259
      IF(ABS(Q-G).LT.1.0E-4) GØ TØ 4010
      Q=G
      GØ TØ 4000
 4010 IG=G
      G=IG
 4015 X2=(.9989+.017*(G/10.0-1.0))*10.0**(G/10.0-4.0)
      D3=SQRT(1.0371E-5/X2)
      IF(G.GT.40.0) GØ TØ 4020
      X3=(.460655*ALØG(D3*1.E3)-.43444)*1.E-3
      GØ TØ 4030
 4020 X3=(98.02228*D3+2.56791E-2)*1.E-3
 4030 ID=(RLN/(D3+X3))
      D=ID
      IE=(D2-D1)/(D3+X3)
      E=IE
      IF(N1.EQ.-1) GØ TØ 4040
      T5=D*E
 4040 RES=T5*X2*(D2+D1)*PI/12.0
      RETURN
      END
```

```
      SUBRØUTINE CIRCT(TMAG,PHASE,Q0,T1,T2)
      CØMMØN /B1/R1,R2,R3,R4,RL3,RL4,R0,R6,R7,R9,C6,C7,V0,GAIN
      CØMMØN /B1/W,FREQ,RBAR,TURNS1,TURNS2/B2/TMUT,DRIVER
      CØMMØN /B2/PICKUP,AIR1,AIR2
      CØMPLEX TMUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
      CØMPLEX DENØM,TNUM,VØLT
      DIMENSIØN TMUT(3,5),DRIVER(3,5),PICKUP(3,5)
      DIMENSIØN TMAG(3,5),PHASE(3,5)
      T1=TURNS1/((R2-R1)*RL3)
      T2=TURNS2/((R4-R3)*RL4)
      Q0=6.300475204E-7*FREQ*RBAR
      Z1=CMPLX(W*R0*C6,-1.0)
      Z2=CMPLX(W*R9*C7,-1.0)
      Z3=CMPLX(0.0,-R0)
      Z4=CMPLX(0.0,-R9)
      DØ 5000 I=1,3
      DØ 5000 J=1,5
      Z5=Q0*T1*T2*TMUT(I,J)
      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(I,J)+AIR1)
      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
      DENØM=Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*
     5 (Z2*(Z7+R7)+Z4)
      TNUM=V0*R9*GAIN*(0.0,-1.0)*Z5
      VØLT=TNUM/DENØM
      TMAG(I,J)=CABS(VØLT)
 5000 PHASE(I,J)=ATAN2(AIMAG(VØLT),REAL(VØLT))
      RETURN
      END
      SUBRØUTINE CIRCT1(Q1,V1,Ø,RAD,SEN)
      DIMENSIØN Ø(3,5),TMAG(3,5),PHASE(3,5)
      CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
      Q1=0.0
      DØ 6000 I=1,3
      DØ 6000 J=1,5
      Q2=Q1-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
     1+PHASE(I,J)-Ø(I,J)
      IF(ABS(Q1).GT.ABS(Q2)) GØ TØ 6000
      Q1=Q2
 6000 CØNTINUE
      Q2NEW=RAD*Q1
      Q3=100.0*Q1/SEN
      TYPE 6010,Q1,Q2NEW,Q3
 6010 FØRMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
      RETURN
      END
```

REFLECTION COIL ABOVE MULTIPLE CONDUCTORS, CONDUCTIVITY VARIATION

We shall now consider the case of a reflection coil above multiple conductors, as shown in Fig. 4 (p. 7). This program calculates the magnitude and phase of the voltage that is fed to the phase measuring circuits of the phase sensitive eddy-current instruments and is designed to help analyze eddy-current measurements of conductivity.

The program calculates the magnitude and phase of the induced voltage at 5 different values of lift-off for each of 3 different conductivity values of a specific conductor, making a total of 15 calculations. This allows one to examine the sensitivity to lift-off variations as well as conductivity variations of the specific conductor. In addition, the program also calculates the phase shift with the discriminator adjusted to give the same phase on the nominal conductivity sample with maximum and minimum lift-off. The phase on the nominal conductivity sample with minimum lift-off is taken as zero, and all other phase shifts are measured relative to it.

The equations which are evaluated are Eq. (8) for the mutual coupling, Eq. (9) for the driver coil impedance, and Eq. (17) for the pickup coil impedance. The gamma factor for multiple conductors is calculated from Eqs. (24) to (28).

The programs are written in both BASIC and FORTRAN for use on the PDP-10. The BASIC program follows.

To use this program, MULTIC (BASIC), one must first divide all dimensions by the mean radius of the driver coil. Then the following lines must be typed into the program.

```
250     R5 = (numerical value of driver coil mean radius in inches)
260     R1 = (numerical value of normalized driver coil inner radius)
270     R2 = (numerical value of normalized driver coil outer radius)
280     L3 = (numerical value of normalized driver coil length)
290     R3 = (numerical value of normalized pickup coil inner radius)
300     R4 = (numerical value of normalized pickup coil outer radius)
310     L4 = (numerical value of normalized pickup coil length)
320     L5 = (numerical value of normalized pickup coil recess from
             face of driver)
```

330 L6 = (numerical value of normalized driver coil minimum lift-off)

340 R6 = (numerical value of resistance of driver coil in ohms)

350 R7 = (numerical value of total resistance of both pickup coils in ohms)

360 N3 = (number of turns on driver coil)

370 N4 = (number of turns on each pickup coil)

380 RO = (output series resistance of driving amplifier in ohms)

390 R9 = (input shunt resistance of pickup amplifier in ohms)

400 C6 = (total shunt capacitance in driving circuit in farads)

410 C7 = (total shunt capacitance in pickup circuit in farads)

420 VO = (output voltage of driving amplifier in volts)

430 G5 = (gain of pickup amplifier)

440 F = (operating frequency in Hertz)

450 L2 = (numerical value of normalized driver coil lift-off increment)

510 N9 = (total number of conductors + 1)

520 N8 = (number of the specific conductor with conductivity variation, refer to Fig. 4)

670 MO = (numerical value of fractional conductivity change of the N8-th layer)

The input data of conductors are typed into the program between the statement numbers 800 and 980, according to the order of appearance from the lowest conductors [refer to Fig. 4 (p. 7)].

```
800      DATA  1E10, K(1), U(1)
810      DATA  T(2), K(2), U(2)
 .         .
 .         .
 .         .
 .       DATA  T(N), K(N), U(N)
 .         .
 .         .
 .         .
 .       DATA  T(N9-1), K(N9-1), U(N9-1)
(980)    DATA  1(arbitrary number), 1E10, 1
```

where

T(N) = numerical value of thickness of the Nth layer conductor in inches,

K(N) = numerical value of resistivity of the Nth layer conductor in microhm centimeters,

U(N) = numerical value of relative permeability of the Nth layer conductor, and

the (N9–1)th layer denotes the top or surface layer.

The current version of MULTIC (BASIC) is limited to a maximum of nine conductors. However, this limitation can be removed easily by adding one DIMENSION statement.

```
60 DIM T(N9), R(N9), U(N9), S(N9), X(N9), Y(N9) .
```

The program may now be run. The print-out by the computer will have the following format.

```
N              THICK(INCH)      R(MU-OHM CM)  M,SIGMA         U
(1)            (T(1))           (K(1))        .......         (U(1))
(2)            (T(2))           (K(2))        .......         (U(2))
 :               :                :             :               :
(N9-1)         (T(N9-1))        (K(N9-1))     .......         (U(N9-1))
(N9)           (T(N))           (K(N))        .......         (U(N))
CONDUCTIVITY VARIATION OF (N8)TH LAYER IS + -(100*MO)%
R1= (R1)       R2= (R2)         DRIVER LENGTH IS (L3)
R3= (R3)       R4= (R4)         PICK UP LENGTH IS (L4)
COIL MEAN RADIUS (R5) INCHES                  OPERATING FREQUENCY (F)
PICK UP RECESSED (L5)
MINIMUM LIFT-OFF (L6)  LIFT-OFF INCREMENT (L2)
DRIVER RES     INCHUCTANCE      NO TURNS      SHUNT CAP       NOR IM PT
  (R6)          ......           (N3)          (C6)            .....
PICKUP RES     INDUCTANCE       NO TURNS      SHUNT CAP       NOR IM PT
  (R7)          ......           (N4)          (C7)            .....
DRIVING VOLT   SERIES RES       AMP GAIN      INPUT IMP
  (V0)           (R0)            (G5)          (R9)
DISCRIMINATOR VOLTAGE IS .....

  (L6)           (L6+L2)          (L6+2L2)      (L6+3L2)        (L6+4L2)

 .....           .....            .....         .....           .....
 .....           .....            .....         .....           .....
 .....           .....            .....         .....           .....

 .....           .....            .....         .....           .....
 .....           .....            .....         .....           .....
   0             .....            .....         .....           .....
```

```
.....          .....          .....          .....          .....
.....          .....          .....          .....          .....
.....          .....          .....          .....          .....
PHASE SHIFT .....  LIFT-OFF .....
DEGREE .....                .....
1 COIL DESIGN   2 ATTEN. DESIGN   3 DRIFT CHECK   4 CON CAL
 ?
```

The various symbols enclosed in parentheses are used to indicate that the numerical value of the symbol will be printed.

There are five columns of data, one under each value of lift-off. Each column is divided into three sections of three lines each. These sections correspond, from top to bottom, to the three values (−100*M0, 0, and +100*M0% variations from nominal) of the conductivity of the N8-th layer. The three lines in each section are, from top to bottom, the magnitude of the voltage out of the pickup amplifier, the phase shift between the voltage out of the pickup amplifier and the driving voltage, and the phase shift between the voltage out of the pickup amplifier with the discriminator set to give the same phase shift with minimum lift-off and maximum lift-off on the nominal conductivity sample. The phase shift in the third line is always measured from the nominal conductivity sample with minimum lift-off. The voltage out of the pickup amplifier will be in volts and be either peak-to-peak or RMS, whichever is used for V0, the output voltage of the driving amplifier. For each conductor N, the value of a dimensionless product $R_5{}^2\omega\mu_N\sigma_N$ is also calculated and printed under the column M,SIGMA. The inductance in henries of the driving coil in air and the normalized imaginary part of the driving coil impedance are also printed, with nominal conductivity and nominal lift-off (L6+2L2). The inductance in henries of both pickup coils in air and the normalized imaginary part of the pickup coils' impedance with nominal conductivity and lift-off is also printed. The total phase shift for the 200*M0% conductivity variation, the maximum phase shift due to lift-off and the maximum percent of range error in conductivity measurements due to lift-off are given. The phase shifts are given first in radians and then in degrees.

The program then enters a branching loop that allows the following options, depending on which of 1, 2, 3, or 4 is typed as input after the question mark.

1. Coil Design

If a 1 is typed by the operator after the question mark, the program will enter the Coil Design Loop. This loop will allow the number of turns on the driver and pickup coils to be varied. The loop will allow the wire gage to be given and then calculate the number of turns and coil resistance, or it will allow the number of turns to be entered and calculate the gage and coil resistance, or both turns and gage can be entered. If zeros are entered for both the gage and turns of either the driver or pickup coils, the present value of these will be retained. The program then starts with the label

DRIVER RES INDUCTANCE NO TURNS SHUNT CAP NOR IM PT ,

and the remainder of the program is recalculated and printed, with the "new" coil in the circuit. However, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

2. Attenuator Design

This loop will allow the driver series resistance, R0, the driver shunt capacitance, C6, the amplifier input impedance, R9, and the shunt capacitance in the pickup circuit, C7, to be varied. If a 2 is typed after the question mark, the computer will respond with

DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP .

The resistance is to be given in ohms, and the capacitance in farads. If zero is typed in for any value, the present value in the computer will be retained. After the input data and a carriage return are typed, the computer will calculate the ratio of resonant frequency to operating frequency for the particular L-C circuit, a very rough value of resistance for minimum temperature drift, and the ratio between the resistance and reactance in the circuit for both the driver and pickup circuits. The program then starts with the label

DRIVER RES INDUCTANCE NO TURNS SHUNT CAP NOR IM PT ,

and the remainder of the program is recalculated and printed with the "new" attenuator in the circuit. Again, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

3. Drift Check

This loop calculates the effect of the drift of any of the circuit or sample parameters after the instrument has been calibrated and adjusted. If a 3 is typed as input, the program will respond with the percent variation, the parameter varied, the maximum change in phase (both radians and degrees) of any of the 15 different phases calculated (5 lift-off values for each of 3 different conductivity values) and the percent of the range the drift represents. The percent variation of each parameter may be varied independently. The following table gives the parameter, the line number, and the constant to be varied:

Parameter	Line Number	Constant
Driver Resistance	8610	E1
Pickup Resistance	8620	E2
Driver Shunt Cap.	8630	E3
Pickup Shunt Cap.	8640	E4
Series Resistance	8650	E7
Amp. Input Resistance	8660	E8
Applied Voltage	8670	E9
Frequency	8680	A1
Mean Radius	8690	A2

For example, to put in a 2% variation in the driver coil resistance, one would type:

8610 E1 = .02

The amount that each parameter is varied must be set before the program is run. All of the variations are 0.01 or 1% in the current version of the program. Since the phase shift produced by the parameter variation is quite linear over a range of about 10%, a linear interpolation or extrapolation may be used from the 1% parameter variation. If zero is typed in for any parameter variation, that parameter will not be varied nor will it be typed out in the list of parameter variations. When the calculation is completed and the drifts printed, the program returns to the branch point and repeats the question

1 Coil Design 2 Atten. Design 3 Drift Check 4 Con Cal .

The first seven drifts do not require that the numerical integrations to calculate M, Z_{DR}, and Z_{PU} be repeated, but they must be repeated to calculate the drifts due to frequency and mean radius changes. Therefore, the calculation of these last two drifts requires a considerable amount of computer time.

4. Con Cal

This loop is to continue calculations. If a series of calculations is to be made, a loop may be established at this point. However, in the present version of the program, if a 4 is typed as input, the program will end.

Sample Calculation of MULTIC

Let us suppose we wish to design a reflection-type coil to measure the conductivity variation of a cladding material that has a thickness of 28 mils and a nominal resistivity of 3.632 μΩ-cm. Below the surface cladding, the next conductor is 194 mils thick and has a resistivity of 5.393 μΩ-cm. Finally, there is another layer of cladding material, with a thickness of 28 mils and resistivity of 3.632 μΩ-cm. The driver coil has a mean radius of 0.08325 in., inner and outer radii of 0.0625 and 0.104 in., and a length of 0.03 in. The pickup coils have inner and outer radii of 0.03 and 0.058 in., a length of 0.008 in. and are mounted flush with the ends of the driver coil. The driver coil has 360 turns of No. 46 wire with a resistance of 79.36 Ω, and the pickup coils have 410 turns each of No. 54 wire, with a resistance of 530.5 Ω for both coils. The driver series and the pickup amplifier input resistances are both chosen to be 1 MΩ. The shunt capacitances in both circuits are chosen to be 1 pF. This corresponds to practically infinite source and detector impedances, so that only the mutual coupling, M, affects the phases. The minimum lift-off is taken to be 0.0083 in. with a lift-off increment of 0.002 in. The variation in the conductivity of the surface cladding is ±5%. The relative permeability of all layers is 1. The frequency is 10,000 Hz, the output voltage of the driving amplifier is 10 V, and the gain of the pickup amplifier is unity (a unity gain allows the actual gain needed in the amplifier to be calculated by dividing the maximum output voltage with unity gain into 10).

The program MULTIC is assumed to be in the active core, and the following information is typed into the computer. All linear dimensions are normalized by dividing by the coil mean radius, except for the coil mean radius, which is in inches.

```
250     R5 = .08325
260     R1 = .75
270     R2 = 1.25
280     L3 = .36
290     R3 = .36
300     R4 = .696
310     L4 = .096
320     L5 = 0
330     L6 = .1
340     R6 = 79.36
350     R7 = 530.5
360     N3 = 360
370     N4 = 410
380     R0 = 1E6
390     R9 = 1E6
400     C6 = 1E-12
410     C7 = 1E-12
420     V0 = 10
430     G5 = 1
440     F = 10000
450     L2 = .025
510     N9 = 5
520     N8 = 4
670     M0 = -.05
```

```
800     DATA  1E10, 1E10, 1
810     DATA  .028, 3.632, 1
820     DATA  .194, 5.393, 1
830     DATA  .028, 3.632, 1
840     DATA  1, 1E10, 1
```

The program may now be run with the following results. The data inputed from the terminal by the user are underlined. A carriage return must be typed by the user at the end of each input line.

```
MULTIT(BASIC)

N              THICK(INCH)    R(MU-ØHM CM)   M,SIGMA        U
 1              1.00000E+10    1.00000E+10    0              1
 2              0.028          3.632          9.72034        1
 3              0.194          5.393          6.54632        1
 4              0.028          3.632          9.72034        1
 5              1              1.00000E+10    0              1
THICKNESS VARIATIØN ØF 4 TH LAYER IS +- 5 %
R1= 0.75       R2= 1.25       DRIVER LENGTH IS 0.36
R3= 0.36       R4= 0.696      PICK UP LENGTH IS 0.096
CØIL MEAN RADIUS 8.32500E-2 INCHES     ØPERATING FREQUENCY 10000
PICK UP RECESSED 0
MIN LIFT-ØFF= 0.1 LIFT-ØFF INCREMENT= 0.025
DRIVER RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 79.36          6.05067E-4     360            1.00000E-12    0.849616
PICKUP RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 530.5          4.72124E-4     410            1.00000E-12    0.992308
DRIVING VØLT   SERIES RES     AMP GAIN       INPUT IMP
 10             1000000        1              1000000
DISCRIMINATØR VØLTAGE IS-6.34033E-7

 0.1            0.125          0.15           0.175          0.2

 1.31981E-5     1.21111E-5     1.11162E-5     1.02067E-5     9.37604E-6
-0.802613      -0.806757      -0.811479      -0.816683      -0.822288
 3.52971E-3     3.70328E-3     3.67406E-3     3.56159E-3     3.47065E-3

 1.32201E-5     1.21309E-5     1.11340E-5     1.02228E-5     9.39059E-6
-0.806063      -0.810183      -0.814884      -0.820068      -0.825654
 0              1.91204E-4     1.77376E-4     7.85962E-5     0

 1.32375E-5     1.21466E-5     1.11481E-5     1.02355E-5     9.40206E-6
-0.809286      -0.813385      -0.818065      -0.82323       -0.828799
-3.28648E-3    -3.07799E-3    -3.07622E-3    -3.16116E-3    -3.22723E-3
PHASE SHIFT 6.75367E-3 LIFT-ØFF 2.32629E-4 IN % 3.44449
IN DEGREE 0.386957            1.33287E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?1
```

```
DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS
 ?46,0,54,0
DRIVER 391 TURNS ØF # 46 WIRE 17 /LAYER 23 LAYERS 71.9293 ØHM
PICKUP 429 TURNS EA # 54 WIRE 11 /LAYER 39 LAYERS 532.582 ØHMS TØTAL
DRIVER RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 71.9293       7.13760E-4     391            1.00000E-12    0.849616
PICKUP RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 532.582       5.16896E-4     429            1.00000E-12    0.992308
DRIVING VØLT   SERIES RES     AMP GAIN       INPUT IMP
 10            1000000        1              1000000
DISCRIMINATØR VØLTAGE IS-7.20555E-7

 0.1           0.125          0.15           0.175          0.2

 1.49990E-5    1.37636E-5     1.26329E-5     1.15993E-5     1.06554E-5
-0.802621     -0.806765      -0.811487      -0.816691      -0.822297
 3.52971E-3    3.70328E-3     3.67405E-3     3.56157E-3     3.47065E-3

 1.50239E-5    1.37861E-5     1.26532E-5     1.16176E-5     1.06719E-5
-0.806071     -0.810191      -0.814892      -0.820076      -0.825662
 0             1.91189E-4     1.77369E-4     7.85962E-5    -7.45058E-9

 1.50438E-5    1.38040E-5     1.26693E-5     1.16321E-5     1.06850E-5
-0.809294     -0.813393      -0.818073      -0.823238      -0.828807
-3.28647E-3   -3.07799E-3    -3.07623E-3    -3.16116E-3    -3.22720E-3
PHASE SHIFT 6.75367E-3 LIFT-ØFF 2.32629E-4 IN % 3.44449
IN DEGREE 0.386957            1.33287E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?2
```

```
DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP
 ?5.0E2,4.7E-9,6.2E2,4.7E-9
DVR CT 9.42723 BELØW RES 359.202 ØPT RES 13.1225 RES/REACTANCE
P-U CT 10.2505 BELØW RES 330.351 ØPT RES 19.2381 RES/REACTANCE
DRIVER RES     INDUCTANCE     NØ TURNS      SHUNT CAP     NØR IM PT
 71.9293        7.13760E-4     391           4.70000E-9    0.849616
PICKUP RES     INDUCTANCE     NØ TURNS      SHUNT CAP     NØR IM PT
 532.582        5.16896E-4     429           4.70000E-9    0.992308
DRIVING VØLT   SERIES RES     AMP GAIN      INPUT IMP
 10             500            1             620
DISCRIMINATØR VØLTAGE IS-7.81534E-4

 0.1            0.125          0.15          0.175         0.2

 1.40412E-2     1.28960E-2     1.18459E-2    1.08844E-2    1.00052E-2
-1.00003       -1.00497       -1.01043      -1.01633      -1.02257
 3.49556E-3     3.50292E-3     3.42207E-3    3.37109E-3    3.45401E-3

 1.40649E-2     1.29174E-2     1.18652E-2    1.09019E-2    1.00209E-2
-1.00343       -1.00835       -1.0138       -1.01967      -1.0259
 0              2.02060E-5    -4.97103E-5   -9.12398E-5    0

 1.40839E-2     1.29344E-2     1.18805E-2    1.09157E-2    1.00333E-2
-1.00661       -1.01152       -1.01694      -1.0228       -1.02902
-3.25559E-3    -3.22221E-3    -3.28045E-3   -3.31177E-3   -3.21142E-3
PHASE SHIFT 6.70542E-3 LIFT-ØFF 1.31831E-4 IN % 1.96603
IN DEGREE 0.384192             7.55334E-3
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?3

SYSTEM DRIFT VARIATIØNS
% VARIATN      PARAMETER      RADIAN        DEGREE        % ØF RANGE
 1             DRIVER RES      2.46316E-5    1.41129E-3    0.367339
 1             PICKUP RES     -5.91874E-5   -3.39119E-3   -0.88268
 1             DVR SHUNT CAP  -2.10896E-4   -1.20835E-2   -3.14516
 1             P-U SHUNT CAP  -8.43331E-4   -4.83194E-2   -12.5769
 1             SERIES RES      1.23148E-3    7.05585E-2    18.3654
 1             AMP INPUT RES  -5.98446E-4   -3.42884E-2   -8.92481
 1             APPLIED VØLT   -7.75740E-4   -4.44466E-2   -11.5688
 1             FREQUENCY      -6.05841E-3   -0.347122     -90.351
 1             MEAN RADIUS    -7.58457E-3   -0.434564     -113.111
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?4
```

The user has exercised all the design options available, and these options may be repeated, omitted, or taken in any order. The BASIC version of the program MULTIC follows.

```
1   REM MULTIC(BASIC)
10 REM REFLECTION COIL FOR CONDUCTIVITY VARIATION  OF
20 REM MULTILAYER CONDUCTORS
40 DIM A(3,5),B(3,5),C(3,5),D(3,5),E(3,5),F(3,5)
50 DIM M(3,5),P(3,5),Q(3,5)
199 REM CONSTANT
200 P9=3.14159
210 P8=180/P9
249 REM COIL DATA
250R5=.08325
260R1=.75
270R2=1.25
280L3=.36
290R3=.36
300R4=.696
310L4=.096
320L5=0
330L6=.1
340R6=79.36
350R7=530.5
360N3=360
370N4=410
379 REM CIRCUIT DATA
380R0=1E6
390R9=1E6
400C6=1E-12
410C7=1E-12
420V0=10.0
430G5=1
440F=10E3
450L2=.025
470L7=L3-2*(L4+L5)
480L8=L7+L4
490L9=L5+2*L6
499 REM CONDUCTOR DATA
500 DIM K(3),N(3),L(5)
510 N9=5
520 N8=4
529 REM READ T,K,U
530 PRINT "N","THICK(INCH)","R(MU-OHM CM)","M,SIGMA","U"
535 FOR N=1 TO N9
537 READ T(N),R(N),U(N)
539 NEXT N
540 GO SUB 600
550 FOR N=1 TO N9
560 PRINT N,T(N),R(N),S(N),U(N)
570 NEXT N
580 GO TO 750
599 REM SUBROUTINE FOR M
600 W=2*P9*F
610 FOR N=1 TO N9
630 S(N)=0
640 IF R(N)>1E9 THEN 660
650 S(N)=.5094*U(N)*F*R5*R5/R(N)
660 NEXT N
670 M0=-.05
680 FOR I=1 TO 3
```

```
690 M(I,0)=S(N8)*(1-(I-2)*M0)
700 NEXT I
710 RETURN
750 T(N9)=0
780 PRINT "CØNDUCTIVITY VARIATIØN ØF";N8;"TH LAYER IS +-";100*M0;"%"
799 REM DATA
800 DATA 1E10,1E10,1
810 DATA .028,3.632,1
820 DATA .194,5.393,1
830 DATA .028,3.632,1
840 DATA 1,1E10,1
999 REM PRINT CØIL DATA
1000 PRINT "R1=";R1,"R2=";R2,"DRIVER LENGTH IS";L3
1010 PRINT"R3=";R3,"R4=";R4,"PICK UP LENGTH IS";L4
1020 PRINT "CØIL MEAN RADIUS";R5;"INCHES     ØPERATING FREQUENCY";F
1030 PRINT "PICK UP RECESSED";L5
1040 PRINT "MIN LIFT-ØFF=";L6;"LIFT-ØFF INCREMENT=";L2
1100 REM PRØGRAM BEGINS
1110 REM FØR INTEGRATIØNS
1120 GØ SUB 1500
1130 REM FØR INDUCTANCES AND CIRCUIT; MAGNITUDE AND PHASE
1140 GØ SUB 6000
1150 REM FØR DISCRIMINATØR VØLTAGE AND PHASE SHIFT
1160 GØ SUB 6500
1170 REM FØR PRINTING ØF RESULTS
1180 GØ SUB 6700
1190 REM FØR AV. PHASE SHIFT AND LIFT-ØFF ERRØR
1200 GØ SUB 7000
1400 REM FØR CØIL AND ATTENUATØR DESIGNS, AND DRIFT
1410 GØ TØ 7200
1499 REM SUBRØUTINE FØR INTEGRATIØN
1500 A3=0
1510 A4=0
1520 FØR I=1 TØ 3
1530 FØR J=1 TØ 5
1540 A(I,J)=0
1550 B(I,J)=0
1560 C(I,J)=0
1570 D(I,J)=0
1580 E(I,J)=0
1590 F(I,J)=0
1600 NEXT J
1610 NEXT I
1620 LET S2=5
1630 B1=0
1640 B2=5
1650 S1=1E-2
1660 FØR X=B1+S1/2 TØ B2 STEP S1
1670 GØ SUB 2000
1680 NEXT X
1690 B1=B2
1700 B2=B2+S2
1710 S1=.05
1720 IF X<9 THEN 1660
1730 S1=.1
1740 IF X<29 THEN 1660
1750 S1=.2
1760 IF X<39 THEN 1660
```

```
1770 S1=.5
1780 IF X<79 THEN 1660
1790 RETURN
1998 REM SUBRØUTINE FØR L-FACTØR AND INTEGRANTS
1999 REM FØR J-FACTØR
2000 GØ SUB 2700
2010 W5=0
2020 W2=0
2030 W6=0
2040 W7=0
2050 W4=1
2060 W8=1
2070 W3=1
2080 IF X*L5>20 THEN 2100
2090 W5=EXP(-X*L5)
2100 IF X*L2>20 THEN 2120
2110 W2=EXP(-X*L2)
2120 IF X*L6>20 THEN 2140
2130 W6=EXP(-X*L6)
2140 IF X*L7>20 THEN 2160
2150 W7=EXP(-X*L7)
2160 IF X*L4>15 THEN 2220
2170 W4=1-EXP(-X*L4)
2180 IF X*L8>15 THEN 2220
2190 W8=1-EXP(-X*L8)
2200 IF X*L3>15 THEN 2220
2210 W3=1-EXP(-X*L3)
2220 IF X>30 THEN 2460
2230 IF X*L9>20 THEN 2460
2240 A5=W6*W6*W3*W4*W5*W8*S3
2250 A6=W6*W6*W3*W3*S4
2260 A7=W6*W6*W4*W4*W5*W5*W8*W8*S5
2270 L(1)=1
2280 FØR J=2 TØ 5
2290 L(J)=0
2300 IF J*X*L2>20 THEN 2320
2310 L(J)=W2*L(J-1)
2320 NEXT J
2329 REM FØR GAMMA FACTØR
2330 GØ SUB 3200
2340 FØR I=1 TØ 3
2350 FØR J=1 TØ 5
2360 Q1=K(I)*L(J)*L(J)
2370 Q2=-N(I)*L(J)*L(J)
2380 A(I,J)=A(I,J)+Q2*A5
2390 B(I,J)=B(I,J)+Q1*A5
2400 C(I,J)=C(I,J)+Q2*A6
2410 D(I,J)=D(I,J)+Q1*A6
2420 E(I,J)=E(I,J)+Q2*A7
2430 F(I,J)=F(I,J)+Q1*A7
2440 NEXT J
2450 NEXT I
2460 A3=A3+2*(X*L3-W3)*S4
2470 A4=A4+(4*(X*L4-W4)-2*W7*W4*W4)*S5
2480 RETURN
2699 REM SUBRØUTINE FØR J5=J(R1,R2)/X↑3,J6=J(R3,R4)/X↑3
2700 R=R1
```

```
2710 GØ SUB 2900
2720 J1=02
2730 R=R2
2740 GØ SUB 2900
2750 J5=02-J1
2760 R=R3
2770 GØ SUB 2900
2780 J3=02
2790 R=R4
2800 GØ SUB 2900
2810 J6=02-J3
2820 S3=S1*J5*J6
2830 S4=S1*J5*J5
2840 S5=S1*J6*J6
2850 RETURN
2899 REM SUBRØUTINE FØR Q2=J(R,0)*X↑3
2900 Z=X*R
2910 IF Z>5 THEN 3000
2920 Q1=R*R*R/2
2930 Q2=Q1/3
2940 Q3=INT(2*Z)+3
2950 FØR Q=1 TØ Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 GØ TØ 3050
3000 Q1=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
3010 Q1=((Q1-0.1730503)/Z+0.7034845)/Z-0.064109E-3
3020 Q2=(((-5.817517/Z+2.105874)/Z-0.6896196)/Z+0.4952024)/Z
3030 Q2=(Q2-0.187344E-2)/Z+0.7979095
3040 Q2=(1-SQR(Z)*(Q2*CØS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3198 REM SUBRØUTINE FØR GAMMA FACTØR(K(I),N(I))
3199 REM FØR BETA(X1,Y1)N
3200 Q1=X*X
3210 Q2=Q1*Q1
3220 Q=0
3230 N=N9
3240 M1=S(N)
3250 U1=U(N)
3260 GØ SUB 5000
3270 X(N)=X1
3280 Y(N)=Y1
3290 Q=Q+X1*T(N)/R5
3300 IF Q>20 THEN 3340
3310 IF N=1 THEN 3340
3320 N=N-1
3330 GØ TØ 3240
3340 N7=N
3350  REM FØR CØNDUCTIVITY VARIATIØN
3360 FØR I=1 TØ 3
3370 M1=M(I,0)
3380 U1=U(N8)
3390 GØ SUB 5000
3400 X(I,0)=X1
3410 Y(I,0)=Y1
3420 NEXT I
3430 REM FØR GAMMA FACTØR
```

```
3440 IF N8=N7 THEN 3690
3450 IF N8=N7+1 THEN 3690
3460 N=N7+1
3470 GØ SUB 5100
3480 GØ SUB 5150
3490 N6=N8-1
3500 IF N8=N7+2 THEN 3650
3510 IF N8>N7 THEN3540
3520 N6=N9
3530 IF N7=N9-1 THEN 3980
3540 X0=X(2)
3550 Y0=Y(2)
3560 FØR N=N7+2 TØ N6
3570 X1=X(N)
3580 Y1=Y(N)
3590 GØ SUB 5300
3600 GØ SUB 5580
3610 X0=X1
3620 Y0=Y1
3630 NEXT N
3640 IF N8<N7 THEN 3980
3650 I1=V3
3660 I2=V4
3670 I3=V7
3680 I4=V8
3690 IF N8=N9-1 THEN 3980
3700 REM FØR V(K,M+1)L,I
3710 N=N8+2
3720 GØ SUB 5100
3730 GØ SUB 5300
3740 V1=T1
3750 V2=T2
3760 V3=T3
3770 V4=T4
3780 V5=T5
3790 V6=T6
3800 V7=T7
3810 V8=T8
3820 IF N8=N9-2 THEN 3930
3830 X0=X(N8+2)
3840 Y0=Y(N8+2)
3850 FØR N=N8+3 TØ N9
3860 X1=X(N)
3870 Y1=Y(N)
3880 GØ SUB 5300
3890 GØ SUB 5500
3900 X0=X1
3910 Y0=Y1
3920 NEXT N
3930 I5=V3
3940 I6=V4
3950 I7=V7
3960 I8=V8
3970 REM T(M+1,M)T(M,M-1)I,J
3980 FØR I=1 TØ 3
3990 IF N8<N7 THEN 4380
4000 IF N8=N7 THEN 4160
4010 X0=X(N8-1)
```

```
4020 YO=Y(N8-1)
4030 N=N8
4040 X1=X(I,0)
4050 Y1=Y(I,0)
4060 IF N8=N7+1 THEN 4140
4070 GØ SUB 5300
4080 V3=I1
4090 V4=I2
4100 V7=I3
4110 V8=I4
4120 GØ SUB 5580
4130 GO TØ 4160
4140 GØ SUB 5150
4150 REM T(M+1,M)I,P (T(M,M-1)V(M-1,1))P,2
4160 XO=X(I,0)
4170 YO=Y(I,0)
4180 N=N8+1
4190 X1=X(N)
4200 Y1=Y(N)
4210 IF N8=N7 THEN 4250
4220 GØ SUB 5300
4230 GØ SUB 5580
4240 GØ TØ 4260
4250 GØ SUB 5150
4260 IF N8=N9-1 THEN 4380
4270 REM FØR V(K,M+1)L,I .....
4280 T1=V1
4290 T2=V2
4300 T3=I5
4310 T4=I6
4320 T5=V5
4330 T6=V6
4340 T7=I7
4350 T8=I8
4360 GØ SUB 5580
4370 REM FØR GAMMA FACTØR
4380 V9=V7/V8+V8/V7
4390 K(I)=(V3/V8+V4/V7)/V9
4400 N(I)=(V4/V8-V3/V7)/V9
4410 NEXT I
4420 RETURN
4999 REM SUBRØUTINE FØR BETA(X1,Y1)
5000 IF M1<Q1*1E-5 THEN 5050
5010 Q3=SQR(Q2+M1*M1)
5020 X1=.707106781*SQR(Q3+Q1)/U1
5030 Y1=.707106781*SQR(Q3-Q1)/U1
5040 GØ TØ 5070
5050 X1=X/U1
5060 Y1=0
5070 RETURN
5099 REM SUBRØUTINE FØR INITIAL STEPS
5100 XO=X(N-1)
5110 YO=Y(N-1)
5120 X1=X(N)
5130 Y1=Y(N)
5140 RETURN
5150 V3=X1-XO
5160 V4=Y1-YO
```

```
5170 V7=X1+X0
5180 V8=Y1+Y0
5190 RETURN
5299 REM SUBRØUTINE FØR XFØRMATIØM MATRIX T
5300 Q2=X1+X0
5310 Q1=X1-X0
5320 Q4=Y1+Y0
5330 Q3=Y1-Y0
5340 Q5=U(N-1)*T(N-1)/R5
5350 Q6=EXP(Q5*X0)
5360 Q7=CØS(Q5*Y0)
5370 Q8=SIN(Q5*Y0)
5380 T1=(Q2*Q7+Q4*Q8)/Q6
5390 T2=(Q4*Q7-Q2*Q8)/Q6
5400 T3=(Q1*Q7-Q3*Q8)*Q6
5410 T4=(Q3*Q7+Q1*Q8)*Q6
5420 T5=(Q1*Q7+Q3*Q8)/Q6
5430 T6=(Q3*Q7-Q1*Q8)/Q6
5440 T7=(Q2*Q7-Q4*Q8)*Q6
5450 T8=(Q4*Q7+Q2*Q8)*Q6
5460 RETURN
5499 REM SUBRØUTINE FØR XFØRMATIØN MATRIX V
5500Q1=V1
5510Q2=V2
5520Q5=V5
5530Q6=V6
5540 V1=T1*Q1-T2*Q2+T3*Q5-T4*Q6
5550 V2=T2*Q1+T1*Q2+T4*Q5+T3*Q6
5560 V5=T5*Q1-T6*Q2+T7*Q5-T8*Q6
5570 V6=T6*Q1+T5*Q2+T8*Q5+T7*Q6
5580Q3=V3
5590Q4=V4
5600Q7=V7
5610Q8=V8
5620 V3=T1*Q3-T2*Q4+T3*Q7-T4*Q8
5630 V4=T2*Q3+T1*Q4+T4*Q7+T3*Q8
5640 V7=T5*Q3-T6*Q4+T7*Q7-T8*Q8
5650 V8=T6*Q3+T5*Q4+T8*Q7+T7*Q8
5660 RETURN
5999 REM SUBRØUTINE FØR CIRCUIT, MAGNITUDE, AND PHASE
6000N1=N3/((R2-R1)*L3)
6010N2=N4/((R4-R3)*L4)
6020Q0=6.300475204E-7*F*R5
6030 W1=W*C6*R0
6040 W2=W*C7*R9
6050 W3=1-W1*W2
6060 W4=W1+W2
6070 FØR I=1 TØ 3
6080 FØR J=1 TØ 5
6090Z8=Q0*N1*N2*A(I,J)
6100Z9=Q0*N1*N2*B(I,J)
6110Z=Q0*N1*N1*C(I,J)
6120Z2=Q0*N1*N1*(D(I,J)+A3)
6130Z1=Q0*N2*N2*E(I,J)
6140Z3=Q0*N2*N2*(F(I,J)+A4)
6150 Q1=R0+R6+Z-W1*Z2
6160 Q2=R9+R7+Z1-W2*Z3
6170 Q3=Z2+W1*(R6+Z)
```

```
6180 Q4=Z3+W2*(R7+Z1)
6190 Q5=Z8*Z8-Z9*Z9
6200 Q6=2*Z8*Z9
6210 Q7=Q1*Q2-Q3*Q4-(W3*Q5-W4*Q6)
6220 Q8=Q1*Q4+Q3*Q2-(W4*Q5+W3*Q6)
6230 Q9=Z8*Q7+Z9*Q8
6240 W5=Z9*Q7-Z8*Q8
6250 M(I,J)=G5*R9*V0*SQR(Q9*Q9+W5*W5)/(Q7*Q7+Q8*Q8)
6260 P(I,J)=ATN(W5/Q9)
6270 IF Q9>0 THEN 6290
6280 P(I,J)=P(I,J)+SGN(W5)*P9
6290 NEXT J
6300 NEXT I
6310 RETURN
6499 REM SUBRØUTINE FØR DISC. VØLTAGE AN PHASE SHIFT
6500 Q1=M(2,5)*SIN(P(2,5))-M(2,1)*SIN(P(2,1))
6510 Q2=-M(2,5)*CØS(P(2,5))+M(2,1)*CØS(P(2,1))
6520 Q3=ATN(Q1/Q2)
6530 IF Q2>0 THEN 6550
6540 Q3=Q3+SGN(Q1)*P9
6550 V1=M(2,1)*SIN(Q3+P(2,1))
6555 Ø1=Q3
6556 Ø2=V1
6560 FØR I=1 TØ 3
6570 FØR J=1 TØ 5
6580 O(I,J)=Q3-ATN(V1/SQR(M(I,J)*M(I,J)-V1*V1))+P(I,J)
6590 NEXT J
6600 NEXT I
6610 RETURN
6699 REM SUBRØUTINE FØR PRINTING RESULTS
6700PRINT"DRIVER RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6710PRINTR6,Q0*N1*N1*A3/W,N3,C6,(D(2,3)+A3)/A3
6720PRINT"PICKUP RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6730PRINTR7,Q0*N2*N2*A4/W,N4,C7,(F(2,3)+A4)/A4
6740PRINT "DRIVING VØLT","SERIES RES","AMP GAIN","INPUT IMP"
6750PRINTV0,R0,G5,R9
6760PRINT "DISCRIMINATØR VØLTAGE IS";V1
6770 PRINT
6780 PRINT L6,L6+L2,L6+2*L2,L6+3*L2,L6+4*L2
6790 FØR I=1 TØ 3
6800 PRINT
6810 PRINT M(I,1),M(I,2),M(I,3),M(I,4),M(I,5)
6820 PRINT P(I,1),P(I,2),P(I,3),P(I,4),P(1,5)
6830 PRINT O(I,1),O(I,2),O(I,3),O(I,4),O(I,5)
6840 NEXT I
6850 RETURN
6999 REM SUBRØUTINE FØR AV. PHASE SHIFT AND LIFT-ØFF ERRØR
7000 Q1=O(1,1)
7010 Q2=O(1,1)
7020 FØR J=2 TØ 5
7030 IF O(1,J)<Q1 THEN 7050
7040 Q1=O(1,J)
7050 IF O(1,J)>Q2 THEN 7070
7060 Q2=O(1,J)
7070 NEXT J
7080 O=(O(1,1)+O(1,2)+O(1,3)+O(1,4)+O(1,5))/5
7090 O=O-(O(3,1)+O(3,2)+O(3,3)+O(3,4)+O(3,5))/5
7092 Ø=O
```

```
7100 PRINT"PHASE SHIFT";Q;"LIFT-ØFF";Q1-Q2;"IN %";100*(Q1-Q2)/Q
7110 PRINT"IN DEGREE";Q*P8,(Q1-Q2)*P8
7120 RETURN
7199 REM FØR CØIL DESIGN, ATTENUATØR, DRIFT, AND EXIT
7200PRINT"1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL"
7210INPUT N5
7220PRINT
7230ØN N5 GØ TØ 7300,8200,8600,9900
7299 REM FØR CØIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FØR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 GØ SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER";N3;"TURNS ØF #";G;"WIRE";
7390 PRINT Q7;"/LAYER";Q8;"LAYERS";R6;"ØHM"
7399 REM FØR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
7430 W2=R4
7440 W3=L4
7450 GØ SUB 7510
7460 N4=Q2
7470 R7=2*Q9
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIRE";
7490 PRINT Q7;"/LAYER";Q8;"LAYERS";R7;"ØHMS TØTAL"
7500 GØ TØ 1140
7509 REM SUBRØUTINE FØR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FØR GAGE
7540 G=Q1
7550 IF G>.5 THEN 7640
7560 Q5=.95*SQR((W2-W1)*W3/Q2)
7570 Q6=1.0371E-5/Q5/Q5
7580 G0=40
7590 G=40+10*(LØG(Q6)-LØG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 GØ TØ 7590
7630 G=INT(G)
7639 REM FØR TURN NUMBER AND R6
7640 Q6=(.9989+.017*(G/10-1))*10↑(G/10-4)
7650 Q5=SQR(1.0371E-5/Q6)
7660 IF G> 40 THEN 7690
7670 Q5=(.460655*LØG(Q5*1E3)-.43444)*1E-3+Q5
7680 GØ TØ 7700
7690 Q5=(98.02228*Q5+2.56791E-2)*1E-3+Q5
7700 Q7=INT(W3/Q5)
7710 Q8=INT((W2-W1)/Q5)
7720 IF Q2>.5 THEN 7740
7730 Q2=Q7*Q8
```

```
7740 Q9=Q2*Q6*(W2+W1)*P9/12
7750 RETURN
8199 REM FØR ATTENUATØR DESIGN
8200 PRINT "DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP"
8210 INPUT Q1,Q2,Q3,Q4
8220 IF Q1=0 THEN 8240
8230 R0=Q1
8240 IF Q2=0 THEN 8260
8250 C6=Q2
8260 IF Q3=0 THEN 8280
8270 R9=Q3
8280 IF Q4=0 THEN 8300
8290 C7=Q4
8300 Q1=Q0*N1*N1*(D(2,3)+A3)/W
8310 Q2=Q0*N2*N2*(F(2,3)+A4)/W
8320 PRINT "DVR CT";1/(W*SQR(Q1*C6));"BELØW RES";
8330 PRINT SQR(Q1/C6);"ØPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELØW RES";
8350 PRINT SQR(Q2/C7);"ØPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 GØ TØ 1140
8599 REM FØR DRIFTS
8600 PRINT"SYSTEM DRIFT VARIATIØNS"
8610 E1=.01
8620 E2=.01
8630 E3=.01
8640 E4=.01
8650 E7=.01
8660 E8=.01
8670 E9=.01
8680 A1=.01
8690 A2=.01
8710 PRINT "% VARIATN","PARAMETER","RADIAN","DEGREE","% ØF RANGE"
8720 IF E1=0 THEN 8770
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 GØ SUB 9320
8760 R6=R6/(1+E1)
8770 IF E2=0 THEN 8820
8780 R7=R7*(1+E2)
8790 PRINT 100*E2,"PICKUP RES",
8800 GØ SUB 9320
8810 R7=R7/(1+E2)
8820 IF E3=0 THEN 8870
8830 C6=C6*(1+E3)
8840 PRINT 100*E3,"DVR SHUNT CAP",
8850 GØ SUB 9320
8860 C6=C6/(1+E3)
8870 IF E4=0 THEN 8920
8880 C7=C7*(1+E4)
8890 PRINT 100*E4,"P-U SHUNT CAP",
8900 GØ SUB 9320
8910 C7=C7/(1+E4)
8920 IF E7=0 THEN 8970
8930 R0=R0*(1+E7)
8940 PRINT 100*E7,"SERIES RES",
8950 GØ SUB 9320
8960 R0=R0/(1+E7)
8970 IF E8=0 THEN 9020
```

```
8980 R9=R9*(1+E8)
8990 PRINT 100*E8,"AMP INPUT RES",
9000 GØ SUB 9320
9010 R9=R9/(1+E8)
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VØLT",
9050 GØ SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 GØ SUB 9300
9110 F=F/(1+A1)
9120 IF A2=0 THEN 9170
9130 R5=R5*(1+A2)
9140 PRINT 100*A2,"MEAN RADIUS",
9150 GØ SUB 9300
9160 R5=R5/(1+A2)
9170 GØ TØ 7200
9299 REM SUBRØUTINE FØR DRIFT
9300 GØ SUB 600
9310 GØ SUB 1500
9320 GØ SUB 6000
9330 Q1=0
9340 FØR I=1 TØ3
9350 FØR J=1 TØ 5
9360 Q2=Ø1-ATN(Ø2/SQR(M(I,J)*M(I,J)-Ø2*Ø2))+P(I,J)-Q(I,J)
9370 IF ABS(Q1)>ABS(Q2) THEN 9390
9380 Q1=Q2
9390 NEXT J
9400 NEXT I
9410 PRINT Q1,180*Q1/P9,100*Q1/Ø
9420 RETURN
9900 END
```

MULTIC, FORTRAN Version

The FORTRAN version of MULTIC is very similar to the BASIC version. The line numbers given are only for identification and editing purposes and have no effect on the actual execution of the FORTRAN program. The data must be typed in the seventh column, or six spaces must first be typed. The data are inputed as follows:

00250	R5 = (coil mean radius in inches)
00260	R1 = (normalized inner radius of driver coil)
00270	R2 = (normalized outer radius of driver coil)
00280	L3 = (normalized length of driver coil)
00290	R3 = (normalized inner radius of pickup coil)
00300	R4 = (normalized outer radius of pickup coil)
00310	L4 = (normalized length of pickup coil)
00320	L5 = (normalized length of recess of each pickup coil from the face of the driver coil)
00330	L6 = (normalized minimum lift-off of the driver coil)
00340	R6 = (resistance of driver coil in ohms)
00350	R7 = (resistance of both pickup coils in ohms)
00360	N3 = (number of turns on the driver coil)
00370	N4 = (number of turns on each pickup coil)
00380	R0 = (driver amplifier series resistance in ohms)
00390	R9 = (pickup amplifier shunt resistance in ohms)
00400	C6 = (shunt capacitance of driver circuit in farads)
00410	C7 = (shunt capacitance of pickup circuit in farads)
00420	V0 = (output voltage in volts)
00430	G5 = (amplifier gain)
00440	F = (operating frequency in Hertz)
00450	L2 = (normalized lift-off increment of the driver coil)
00510	N9 = (total number of conductors + 1)
00520	N8 = (number of the specific conductor with conductivity variation)

```
00540      DATA  RHO/(resistivities in microhm-cm)/
00550      DATA  U/(permeabilities)/
00560      DATA  T/(thicknesses in inch)/
00740      MO = (fractional variation of conductivity of the N8-th
                layer)
```

The current version of MULTIC.F4 is limited to a maximum of nine conductors. However, this limitation can be removed easily by changing one DIMENSION statement.

```
00110      DIMENSION  T(N9), U(N9), RHO(N9), M(N9), BETA(N9)
```

The print-out of the FORTRAN version of MULTIC is practically identical to the BASIC version and will not be repeated. The main difference is that the question mark is not printed out when the program is ready to accept data. The Coil Design, Attenuator Design, Drift Check, and Continue Calculations options are the same. The line numbers, constant names, and parameter varied in the drift calculations are as follows:

Line Number	Constant	Parameter Varied
04380	DR1	Driver Resistance
04390	DR2	Pickup Resistance
04400	DR3	Driver Shunt Capacitance
04410	DR4	Pickup Shunt Capacitance
04420	DR5	Series Resistance
04430	DR6	Amplifier Input Resistance
04440	DR7	Applied Voltage
04450	DR8	Frequency
04460	DR9	Mean Radius

For example, to vary the driver resistance by 2% one would type:

```
04380      DR1 = 0.02
```

As in the BASIC version, the last two drifts require that the entire numerical integration be repeated and are relatively long running. If any of the drifts is set equal to zero, it will be omitted from the drift calculations.

Sample Calculation of MULTIC.F4

Let us suppose that we wish to design a reflection type coil, identical to the one designed by the BASIC version. We will put the following data in the program (generally by using the EDIT MULTIC.F4 command on the PDP-10 and inserting the statements). All linear dimensions are normalized by dividing by the coil mean radius, except the coil mean radius, which is in inches.

```
R5 = .08325
R1 = 0.75
R2 = 1.25
L3 = .36
R4 = .36
R4 = .696
L4 = .096
L5 = 0.0
L6 = 0.1
R6 = 79.36
R7 = 530.5
N3 = 360.
N4 = 410.
R0 = 1.E6
R9 = 1.E6
C6 = 1.E-12
C7 = 1.E-12
V0 = 10.0
G5 = 1.0
F = 1.0E4
L2 = 0.025
N9 = 5
N8 = 4
DATA  RHO/1.E10, 3.632, 5.393, 3.632, 1.E10, 5*0./
DATA  U/5*1., 5*0./
DATA  T/1.E10, 2.8E-2, 1.94E-1, 2.8E-2, 1., 5*0./
MO = .05
```

The FORTRAN program may now be executed. The print-out will be essentially identical to the BASIC print-out and will not be repeated. The FORTRAN version of MULTIC follows.

```
C     THIS PRØGRAM EVALUATES THE SENSITIVITY TØ A CØNDUCTIVITY
C     VARIATIØN IN ANY GIVEN LAYER ØF A MULTI-LAYERED
C     MATERIAL
      CØMPLEX BETA0,BETA1,BETA,V,V97,TR,GAMMA,MUT,DRIVER
      CØMPLEX PICKUP,BETA8
      CØMMØN X,Z,Q1,PI/B1/BETA0,BETA1
      CØMMØN /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
      CØMMØN /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
      CØMMØN /B3/PICKUP,AIR1,AIR2/B4/GAGE,XIN,XØUT
      CØMMØN /B4/XLEN,TURNS,N1A,J1,PERLAY,XLAY
      DIMENSIØN T(10),U(10),RHØ(10),M(10),BETA(10)
      DIMENSIØN V(2,2),V97(2,2),TR(2,2),GAMMA(3),DRIVER(3,5)
      DIMENSIØN PICKUP(3,5),RL(5),TMAG(3,5),PHASE(3,5)
      DIMENSIØN SHIFT(3,5),MUT(3,5),M9(3),BETA8(3)
      REAL L2,L3,L4,L5,L6,L7,M,M0,M9,N3,N4
      PI=3.1415926536
      RAD=180.0/PI
C
C
C
C
      JKL=0
C     THE FØLLØWING ARE INPUT DATA FØR THE PARAMETERS ØF
C     THE CØILS,MATERIAL,AND CIRCUIT
      R5=.08325
      R1=0.75
      R2=1.25
      L3=.36
      R3=.36
      R4=.696
      L4=.096
      L5=0.0
      L6=0.1
      R6=79.36
      R7=530.5
      N3=360.
      N4=410.
      R0=1.E6
      R9=1.E6
      C6=1.E-12
      C7=1.E-12
      V0=10.0
      G5=1.0
      F=1.0E4
      L2=0.025
C     N9 IS THE TØTAL NUMBER ØF LAYERS,INCLUDING THE CØIL
C     ZØNE, AND N8 IS THE LAYER WHØSE CØNDUCTIVITY VARIES
C
C
C
      N9=5
      N8=4
      IF(N9.LT.2.ØR.N8.GE.N9) GØ TØ 1010
      DATA RHØ/1.E10,3.632,5.393,3.632,1.E10,5*0./
      DATA U/5*1.,5*0./
      DATA T/1.E10,2.8E-2,1.94E-1,2.8E-2,1.,5*0./
      L7=L3-2.0*(L4+L5)
    5 W=2.0*PI*F
```

```
      IF(JKL.NE.0) GØ TØ 15
      TYPE 10
   10 FØRMAT(1H ,1HN,13X,10HTHICK.(IN),4X,11HR(M-0HM CM),
     13X,7HM,SIGMA,7X,1HU)
   15 DØ 50 I=1,N9
      IF(RHØ(I).GT.1.0E9) GØ TØ 20
      M(I)=0.5094*U(I)*F*R5*R5/RHØ(I)
      GØ TØ 25
   20 M(I)=0.0
   25 IF(JKL.NE.0) GØ TØ 50
   30 TYPE 40,I,T(I),RHØ(I),M(I),U(I)
   40 FØRMAT(1H ,I2,12X,1PE12.5,2X,E12.5,2X,E12.5,2X,0PF6.2)
   50 CØNTINUE
      T(1)=0.0
      T(N9)=0.0
      M0=.05
      DØ 52 I=1,3
      AI=I
   52 M9(I)=M(N8)*(1.0+(AI-2.0)*M0)
      IF(JKL.NE.0) GØ TØ 105
      VAR=100.0*M0
C     THE SYSTEM PARAMETERS ARE PRINTED ØUT
      TYPE 55,N8,VAR
   55 FØRMAT(1H ,25HCØNDUCTIVITY VARIATIØN ØF,I3,14HTH LAYER
     1 IS +-,F6.2,1H%)
      TYPE 470
      TYPE 60,R1,R2,L3
   60 FØRMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
     1F8.5)
      TYPE 70,R3,R4,L4
   70 FØRMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
     1F8.5)
      TYPE 80,R5,F
   80 FØRMAT(1H ,17HCØIL MEAN RADIUS=,F8.5,7H INCHES,3X,
     120HØPERATING FREQUENCY=,1PE12.5)
      TYPE 90,L5
   90 FØRMAT(1H ,15HPICKUP RECESSED,F8.5)
      TYPE 100,L6,L2
  100 FØRMAT(1H ,13HMIN LIFT-ØFF=,F8.5,3X,19HLIFT-ØFF INCREM
     1ENT=,F8.5)
C     THE INTEGRATIØN BEGINS HERE. THE MUTUAL,DRIVER,AND
C     PICKUP INDUCTANCES AND THE AIR VALUES ARE CALCULATED
  105 S1=0.01
      S2=5.0
      B1=0.0
      B2=S2
      DØ 107 I=1,3
      DØ 107 J=1,5
      MUT(I,J)=(0.0,0.0)
      DRIVER(I,J)=(0.0,0.0)
  107 PICKUP(I,J)=(0.0,0.0)
      AIR1=0.0
      AIR2=0.0
  110 I1=(B2-B1)/S1
      X=B1-S1/2.0
      DØ 390 IDX=1,I1
      X=X+S1
```

```
      TEST=X*L3
      IF(TEST.GT.20.0) GØ TØ 120
      W3=EXP(-TEST)
      GØ TØ 130
  120 W3=0.0
  130 W8=1.0-W3
      TEST=X*L4
      IF(TEST.GT.20.0) GØ TØ 140
      W4=EXP(-TEST)
      GØ TØ 150
  140 W4=0.0
  150 W9=1.0-W4
      TEST=X*L7
      IF(TEST.GT.20.0) GØ TØ 160
      W7=EXP(-TEST)
      GØ TØ 170
  160 W7=0.0
  170 W5=EXP(-X*L5)
      W0=1.0-W7*W4
      TEST=X*L6
      IF(TEST.GT.20.0) GØ TØ 385
      W6=EXP(-2.0*TEST)
      Z=X*R2
      Q1=R2
C     SUBRØUTINE BESSEL EVALUATES THE INTEGRAL ØF XJ1(X)
      CALL BESSEL(VAL2)
      Z=X*R1
      Q1=R1
      CALL BESSEL(VAL1)
      Z=X*R4
      Q1=R4
      CALL BESSEL(VAL4)
      Z=X*R3
      Q1=R3
      CALL BESSEL(VAL3)
      S3=S1*(VAL2-VAL1)*(VAL4-VAL3)
      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
      A5=W6*W5*W8*W9*W0*S3
      A6=W6*W8*W8*S4
      A7=W6*W5*W5*W9*W9*W0*W0*S5
      IF(X.GT.30.0) GØ TØ 385
C     THE LØWEST SIGNIFICANT LAYER,N7,IS DETERMINED
      QSUM=0.0
      N=N9
      TEST=X*X*1.0E-5
  180 IF(M(N).LT.TEST) GØ TØ 190
      BETA(N)=CSQRT(CMPLX(X*X,M(N)))/U(N)
      GØ TØ 200
  190 BETA(N)=CMPLX(X,0.0)
  200 QSUM=QSUM+REAL(BETA(N))*T(N)/R5
      IF(QSUM.GT.20.0.ØR.N.EQ.1) GØ TØ 210
      N=N-1
      GØ TØ 180
  210 N7=N
      DØ 220 I=1,3
  220 BETA8(I)=CSQRT(CMPLX(X*X,M9(I)))/U(N8)
      IF(N8.EQ.N7.ØR.N8.EQ.N7+1) GØ TØ 260
```

```
      N=N7+1
      BETA0=BETA(N-1)
      BETA1=BETA(N)
      V(1,2)=BETA1-BETA0
      V(2,2)=BETA1+BETA0
      N6=N8-1
      IF(N8.EQ.N7+2) GØ TØ 250
      IF(N8.GT.N7) GØ TØ 230
      N6=N9
      IF(N7.EQ.N9-1) GØ TØ 300
  230 BETA0=BETA(2)
      IDX1=N7+2
      IF(IDX1.GT.N6) GØ TØ 245
      DØ 240 N=IDX1,N6
      BETA1=BETA(N)
      JUMP=1
      CALL XFØRM(N,TR,R5,U,T)
      CALL MATRIX(JUMP,V,TR)
  240 BETA0=BETA1
  245 IF(N8.LT.N7) GØ TØ 300
  250 V97(1,2)=V(1,2)
      V97(2,2)=V(2,2)
  260 IF(N8.EQ.N9-1) GØ TØ 300
      N=N8+2
      BETA0=BETA(N-1)
      BETA1=BETA(N)
      CALL XFØRM(N,TR,R5,U,T)
      DØ 270 I=1,2
      DØ 270 J=1,2
  270 V(I,J)=TR(I,J)
      IF(N8.EQ.N9-2) GØ TØ 290
      BETA0=BETA(N8+2)
      IDX1=N8+3
      IF(IDX1.GT.N9) GØ TØ 290
      DØ 280 N=IDX1,N9
      BETA1=BETA(N)
      JUMP=0
      CALL XFØRM(N,TR,R5,U,T)
      CALL MATRIX(JUMP,V,TR)
  280 BETA0=BETA1
  290 V97(1,1)=V(1,2)
      V97(2,1)=V(2,2)
  300 DØ 330 I=1,3
      IF(N8.LT.N7) GØ TØ 330
      IF(N8.EQ.N7) GØ TØ 310
      BETA0=BETA(N8-1)
      N=N8
      BETA1=BETA8(I)
      IF(N8.EQ.N7+1) GØ TØ 305
      CALL XFØRM(N,TR,R5,U,T)
      V(1,2)=V97(1,2)
      V(2,2)=V97(2,2)
      JUMP=1
      CALL MATRIX(JUMP,V,TR)
      GØ TØ 310
  305 V(1,2)=BETA1-BETA0
      V(2,2)=BETA1+BETA0
  310 BETA0=BETA8(I)
```

```
      N=N8+1
      BETA1=BETA(N)
      IF(N8.EQ.N7) GØ TØ 315
      JUMP=1
      CALL XFØRM(N,TR,R5,U,T)
      CALL MATRIX(JUMP,V,TR)
      GØ TØ 320
  315 V(1,2)=BETA1-BETA0
      V(2,2)=BETA1+BETA0
  320 IF(N8.EQ.N9-1) GØ TØ 330
      DØ 325 J=1,2
      TR(J,1)=V(J,1)
  325 TR(J,2)=V97(J,1)
      JUMP=1
      CALL MATRIX(JUMP,V,TR)
  330 GAMMA(I)=V(1,2)/V(2,2)
      RL(1)=1.0
      TEST=X*L2
      IF(TEST.GT.20.0) GØ TØ 340
      W2=EXP(-2.0*TEST)
      GØ TØ 350
  340 W2=0.0
  350 DØ 370 K=2,5
      AK=K
      TEST=AK*X*L2
      IF(TEST.GT.20.0) GØ TØ 360
      RL(K)=W2*RL(K-1)
      GØ TØ 370
  360 RL(K)=0.0
  370 CØNTINUE
      DØ 380 J=1,3
      DØ 380 K=1,5
      MUT(J,K)=MUT(J,K)+GAMMA(J)*RL(K)*A5
      DRIVER(J,K)=DRIVER(J,K)+GAMMA(J)*RL(K)*A6
  380 PICKUP(J,K)=PICKUP(J,K)+GAMMA(J)*RL(K)*A7
  385 AIR1=AIR1+2.0*S4*(X*L3-W8)
      AIR2=AIR2+S5*(4.0*(X*L4-W9)-2.0*W7*W9*W9)
  390 CØNTINUE
      B1=B2
      B2=B2+S2
      S1=0.05
      IF(X.LT.9.0) GØ TØ 110
      S1=0.1
      IF(X.LT.29.0) GØ TØ 110
      S1=0.2
      IF(X.LT.39.0) GØ TØ 110
      S1=0.5
      IF(X.LT.79.0) GØ TØ 110
C     THE INTEGRATIØN ENDS HERE
      IF(JKL.NE.0) GØ TØ 780
C     NEXT, THE INDUCTANCES,VØLTAGES,AND PHASE SHIFTS
C     ARE CALCULATED AND PRINTED
  400 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
      CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
      TYPE 410
  410 FØRMAT(1H ,10HDRIVER RES,4X,10HINDUCTANCE,4X,
     18HNØ TURNS,6X,9HSHUNT CAP,5X,9HNØR IM PT)
      Q1=Q0*T1*T1*AIR1/W
```

```
      Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
      Q3=Q0*T2*T2*AIR2/W
      Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
      TYPE 420,R6,Q1,N3,C6,Q2
  420 FØRMAT(1H ,1PE12.5,2X,E12.5,2X,0PF8.1,6X,1PE12.5,
     12X,0PF9.6)
      TYPE 430
  430 FØRMAT(1H ,10HPICKUP RES,4X,10HINDUCTANCE,4X,
     18HNØ TURNS,6X,9HSHUNT CAP,5X,9HNØR IM PT)
      TYPE 420,R7,Q3,N4,C7,Q4
      TYPE 440
  440 FØRMAT(1H ,12HDRIVING VØLT,2X,10HSERIES RES,4X,
     18HAMP GAIN,6X,9HINPUT IMP)
      TYPE 450,V0,R0,G5,R9
  450 FØRMAT(1H ,F5.1,9X,1PE12.5,2X,0PF8.1,6X,1PE12.5)
      TYPE 460,V1
  460 FØRMAT(1H ,22HDISCRIMINATØR VØLTAGE=,1PE12.5)
      TYPE 470
  470 FØRMAT(1H )
      RL(1)=L6
      DØ 480 I=2,5
  480 RL(I)=L2+RL(I-1)
      TYPE 490,RL
  490 FØRMAT(1H ,4(F6.3,8X),F6.3)
      TYPE 470
      DØ 500 I=1,3
      TYPE 510,(TMAG(I,J),J=1,5)
      TYPE 510,(PHASE(I,J),J=1,5)
      TYPE 510,(SHIFT(I,J),J=1,5)
      TYPE 470
  500 CØNTINUE
  510 FØRMAT(1H ,4(1PE12.5,2X),E12.5)
      CALL SENS(SHIFT,RAD,SEN)
C     THE USER NEXT SELECTS ØNE ØF FØUR PØSSIBILITIES
  520 TYPE 530
  530 FØRMAT(' 1 CØIL DESIGN  2 ATTEN.DESIGN  3 DRIFT CHECK
     1  4 CØN CAL')
      TYPE 470
      ACCEPT 540,N5
  540 FØRMAT(I1)
      GØ TØ(550,680,760,1010),N5
C     THE FIRST PØSSIBILITY ALLØWS THE USER TØ ALTER THE
C     CØIL DESIGN BY INPUTTING THE REQUESTED INTEGER DATA
  550 TYPE 560
  560 FØRMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
     1 TURNS')
      TYPE 470
      ACCEPT 570,N1A,N2A,N3A,N4A
  570 FØRMAT(4I)
      IF(N1A*N2A.EQ.0) GØ TØ 580
      GAGE=N1A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      TURNS=N2A
      N3=N2A
      N1A=-1
      J1=1
```

```
      CALL GAGER(R6)
      GØ TØ 600
  580 IF(N1A.EQ.0) GØ TØ 590
      GAGE=N1A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=1
      CALL GAGER(R6)
      N3=TURNS
      GØ TØ 600
  590 IF(N2A.EQ.0) GØ TØ 620
      N3=N2A
      TURNS=N2A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=0
      CALL GAGER(R6)
  600 TYPE 610,TURNS,GAGE,PERLAY,XLAY,R6
  610 FØRMAT(1H ,6HDRIVER,F6.1,10H TURNS ØF#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  620 IF(N3A*N4A.EQ.0) GØ TØ 630
      GAGE=N3A
      TURNS=N4A
      N4=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      R7=2.0*R7
      GØ TØ 650
  630 IF(N3A.EQ.0) GØ TØ 640
      GAGE=N3A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      R7=2.0*R7
      N4=TURNS
      GØ TØ 650
  640 IF(N4A.EQ.0) GØ TØ 670
      N4=N4A
      TURNS=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=0
      CALL GAGER(R7)
      R7=2.0*R7
  650 TYPE 660,TURNS,GAGE,PERLAY,XLAY,R7
  660 FØRMAT(1H ,6HPICKUP,F6.1,10H TURNS EA#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  670 GØ TØ 400
C     THE SECØND PØSSIBILITY ALLØWS THE USER TØ ALTER THE
C     ATTENUATØR DESIGN BY INPUTTING THE DATA REQUESTED IN
```

```
C      E FIELD FØRMAT
  680 TYPE 690
  690 FØRMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
     1 SHUNT CAP')
      TYPE 470
      ACCEPT 700,P1,P2,P3,P4
  700 FØRMAT(4E)
      IF(P1.EQ.0.0) GØ TØ 710
      R0=P1
  710 IF(P2.EQ.0.0) GØ TØ 720
      C6=P2
  720 IF(P3.EQ.0.0) GØ TØ 730
      R9=P3
  730 IF(P4.EQ.0.0) GØ TØ 740
      C7=P4
  740 Q5=1.0/(W*SQRT(Q1*Q2*C6))
      Q6=SQRT(Q1*Q2/C6)
      Q7=R0/(W*Q1*Q2)
      Q8=1.0/(W*SQRT(Q3*Q4*C7))
      Q9=SQRT(Q3*Q4/C7)
      Q10=R9/(W*Q3*Q4)
      TYPE 750,Q5,Q6,Q7
  750 FØRMAT(1H ,7HDVR CKT,1PE12.5,10H BELØW RES,1PE12.5,
     18H ØPT RES,1PE12.5,11H RES/REACT.)
      TYPE 755,Q8,Q9,Q10
  755 FØRMAT(1H ,7HP-U CKT,1PE12.5,10H BELØW RES,1PE12.5,
     18H ØPT RES,1PE12.5,11H RES/REACT.)
      GØ TØ 400
C      THE THIRD PØSSIBILITY ALLØWS THE USER TØ EXAMINE THE
C      EFFECT ØF DRIFTS ØN THE CIRCUIT
  760 TYPE 770
  770 FØRMAT(1H ,23HSYSTEM DRIFT VARIATIØNS)
      DR1=0.01
      DR2=0.01
      DR3=0.01
      DR4=0.01
      DR5=0.01
      DR6=0.01
      DR7=0.01
      DR8=0.01
      DR9=0.01
      GØ TØ 790
  780 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      GØ TØ (970,1000),JKL
  790 TYPE 800
  800 FØRMAT(1H ,11H% VARIATIØN,3X,13HPARAMETER VAR,1X,
     17HRADIANS,7X,7HDEGREES,7X,10H% ØF RANGE)
      IF(DR1.EQ.0.0) GØ TØ 830
      R6=R6*(1.0+DR1)
      DR100=100.0*DR1
      TYPE 820,DR100
  820 FØRMAT(1H ,F4.1,10X,13HDRIVER RES    $)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R6=R6/(1.0+DR1)
  830 IF(DR2.EQ.0.0) GØ TØ 850
      R7=R7*(1.0+DR2)
      DR100=100.0*DR2
      TYPE 840,DR100
```

```
 840 FØRMAT(1H ,F4.1,10X,13HPICKUP RES    $)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     R7=R7/(1.0+DR2)
 850 IF(DR3.EQ.0.0) GØ TØ 870
     C6=C6*(1.0+DR3)
     DR100=100.0*DR3
     TYPE 860,DR100
 860 FØRMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     C6=C6/(1.0+DR3)
 870 IF(DR4.EQ.0.0) GØ TØ 890
     C7=C7*(1.0+DR4)
     DR100=100.0*DR4
     TYPE 880,DR100
 880 FØRMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     C7=C7/(1.0+DR4)
 890 IF(DR5.EQ.0.0) GØ TØ 910
     R0=R0*(1.0+DR5)
     DR100=100.0*DR5
     TYPE 900,DR100
 900 FØRMAT(1H ,F4.1,10X,13HSERIES RES    $)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     R0=R0/(1.0+DR5)
 910 IF(DR6.EQ.0.0) GØ TØ 930
     R9=R9*(1.0+DR6)
     DR100=100.0*DR6
     TYPE 920,DR100
 920 FØRMAT(1H ,F4.1,10X,13HAMP INPUT RES$)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     R9=R9/(1.0+DR6)
 930 IF(DR7.EQ.0.0) GØ TØ 950
     V0=V0*(1.0+DR7)
     DR100=100.0*DR7
     TYPE 940,DR100
 940 FØRMAT(1H ,F4.1,10X,13HAPPLIED VØLT.$)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     V0=V0/(1.0+DR7)
 950 IF(DR8.EQ.0.0) GØ TØ 980
     F=F*(1.0+DR8)
     DR100=100.0*DR8
     TYPE 960,DR100
 960 FØRMAT(1H ,F4.1,10X,13HFREQUENCY     $)
     JKL=1
     GØ TØ 5
 970 F=F/(1.0+DR8)
     JKL=0
 980 IF(DR9.EQ.0.0) GØ TØ 520
     R5=R5*(1.0+DR9)
     DR100=100.0*DR9
     TYPE 990,DR100
 990 FØRMAT(1H ,F4.1,10X,13HMEAN RADIUS  $)
     JKL=2
     GØ TØ 5
1000 R5=R5/(1.0+DR9)
     JKL=0
     GØ TØ 520
C    THE FØURTH PØSSIBILITY ENDS CALCULATIØNS
```

```
1010 CALL EXIT
     END
     SUBRØUTINE BESSEL(VAL)
     CØMMØN X,Z,Q1,PI
     IF(Z.GT.5.0) GØ TØ 1510
     L=2.0*Z+3.0
     F1=0.5*Q1*Q1*Q1
     VAL=F1/3.0
     DØ 1500 I=1,L
     AI=I
     F1=-F1*0.25*Z*Z/(AI*AI+AI)
1500 VAL=VAL+F1/(2.0*AI+3.0)
     GØ TØ 1520
1510 X0=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
     X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
     X1=(((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
     X1=(X1-0.187344E-2)/Z+0.7979095
     VAL=(1.0-SQRT(Z)*(X1*CØS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
    1(X*X*X)
1520 RETURN
     END
     SUBRØUTINE XFØRM(N,TR,R5,U,T)
     CØMMØN /B1/BETA0,BETA1
     CØMPLEX BETA0,BETA1,EX,TR
     DIMENSIØN EX(2),U(10),T(10),TR(2,2)
     EX(1)=CEXP(-BETA0*U(N-1)*T(N-1)/R5)
     EX(2)=1.0/EX(1)
     DØ 1610 I=1,2
     DØ 1610 J=1,2
     K=I+J
     IF(K.EQ.3) GØ TØ 1600
     TR(I,J)=(BETA1+BETA0)*EX(J)
     GØ TØ 1610
1600 TR(I,J)=(BETA1-BETA0)*EX(J)
1610 CØNTINUE
     RETURN
     END
     SUBRØUTINE MATRIX(JUMP,V,TR)
     CØMPLEX V,Q,TR
     DIMENSIØN Q(2,2),V(2,2),TR(2,2)
     IF(JUMP.EQ.1) GØ TØ 1720
     DØ 1700 I=1,2
1700 Q(I,1)=V(I,1)
     DØ 1710 I=1,2
     V(I,1)=(0.0,0.0)
     DØ 1710 J=1,2
1710 V(I,1)=V(I,1)+TR(I,J)*Q(J,1)
1720 DØ 1730 I=1,2
1730 Q(I,2)=V(I,2)
     DØ 1740 I=1,2
     V(I,2)=(0.0,0.0)
     DØ 1740 J=1,2
1740 V(I,2)=V(I,2)+TR(I,J)*Q(J,2)
     RETURN
     END
     SUBRØUTINE CIRCT(TMAG,PHASE,Q0,T1,T2)
     CØMPLEX MUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
     CØMPLEX DENØM,TNUM,VØLT
```

```
      CØMMØN /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
      CØMMØN /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
      CØMMØN /B3/PICKUP,AIR1,AIR2
      DIMENSIØN MUT(3,5),DRIVER(3,5),PICKUP(3,5)
      DIMENSIØN TMAG(3,5),PHASE(3,5)
      REAL L3,L4,N3,N4
      T1=N3/((R2-R1)*L3)
      T2=N4/((R4-R3)*L4)
      Q0=6.300475204E-7*F*R5
      Z1=CMPLX(W*C6*R0,-1.0)
      Z2=CMPLX(W*C7*R9,-1.0)
      Z3=CMPLX(0.0,-R0)
      Z4=CMPLX(0.0,-R9)
      DØ 1800 I=1,3
      DØ 1800 J=1,5
      Z5=Q0*T1*T2*MUT(I,J)
      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(I,J)+AIR1)
      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
      DENØM=Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*(Z2*(Z7+R7)+Z4)
      TNUM=V0*R9*G5*(0.0,-1.0)*Z5
      VØLT=TNUM/DENØM
      TMAG(I,J)=CABS(VØLT)
 1800 PHASE(I,J)=ATAN2(AIMAG(VØLT),REAL(VØLT))
      RETURN
      END
      SUBRØUTINE PHASET(A,B,C,V1,Ø3)
      DIMENSIØN A(3,5),B(3,5),C(3,5)
      Ø1=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
      Ø2=-(A(2,5)*CØS(B(2,5))-A(2,1)*CØS(B(2,1)))
      Ø3=ATAN2(Ø1,Ø2)
      V1=A(2,1)*SIN(Ø3+B(2,1))
      DØ 1900 I=1,3
      DØ 1900 J=1,5
 1900 C(I,J)=Ø3-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(I,J)
      RETURN
      END
      SUBRØUTINE SENS(Ø,RAD,Ø1)
      DIMENSIØN Ø(3,5)
      Ø9=Ø(1,1)
      Ø0=Ø(1,1)
      DØ 2010 I=2,5
      IF(Ø(1,I).LT.Ø9) GØ TØ 2000
      Ø9=Ø(1,I)
 2000 IF(Ø(1,I).GT.Ø0) GØ TØ 2010
      Ø0=Ø(1,I)
 2010 CØNTINUE
      Ø1=(Ø(1,1)+Ø(1,2)+Ø(1,3)+Ø(1,4)+Ø(1,5))/5.0
      Ø1=Ø1-(Ø(3,1)+Ø(3,2)+Ø(3,3)+Ø(3,4)+Ø(3,5))/5.0
      XLØ=Ø9-Ø0
      PERCT=100.0*XLØ/Ø1
      DEGR1=Ø1*RAD
      DEGR2=XLØ*RAD
      TYPE 2020,Ø1,XLØ,PERCT
 2020 FØRMAT(1H ,12HPHASE SHIFT=,1PE12.5,2X,8HLIFTØFF=,
     1E12.5,2X,2H%=,E12.5)
      TYPE 2030,DEGR1,DEGR2
 2030 FØRMAT(1H ,7HDEGREE:,1PE13.5,5X,E13.5)
```

```
      RETURN
      END
      SUBRØUTINE GAGER(RES)
      CØMMØN /B4/G,D1,D2,RLN,T5,N1A,J1,D,E
      PI=3.1415926536
      IF(J1.EQ.1) GØ TØ 2120
      N1A=-1
      D3=0.95*SQRT((D2-D1)*RLN/T5)
      X2=1.0371E-5/(D3*D3)
      Q=40.0
 2100 G=40.0+10.0*(ALØG(X2)-ALØG(.9989+.017*(Q/10.0-1.0)))/2.3
     10259
      IF(ABS(Q-G).LT.1.0E-4) GØ TØ 2110
      Q=G
      GØ TØ 2100
 2110 IG=G
      G=IG
 2120 X2=(.9989+.017*(G/10.0-1.0))*10.0**(G/10.0-4.0)
      D3=SQRT(1.0371E-5/X2)
      IF(G.GT.40.0) GØ TØ 2130
      X3=(.460655*ALØG(D3*1.0E3)-.43444)*1.0E-3
      GØ TØ 2140
 2130 X3=(98.02228*D3+2.56791E-2)*1.0E-3
 2140 ID=(RLN/(D3+X3))
      D=ID
      IE=(D2-D1)/(D3+X3)
      E=IE
      IF(N1A.EQ.-1) GØ TØ 2150
      T5=D*E
 2150 RES=T5*X2*(D2+D1)*PI/12.0
      RETURN
      END
      SUBRØUTINE CIRCT1(Ø1,V1,Ø,RAD,SEN)
      DIMENSIØN Ø(3,5),TMAG(3,5),PHASE(3,5)
      CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
      Q1=0.0
      DØ 2200 I=1,3
      DØ 2200 J=1,5
      Q2=Ø1-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
     1+PHASE(I,J)-Ø(I,J)
      IF(ABS(Q1).GT.ABS(Q2)) GØ TØ 2200
      Q1=Q2
 2200 CØNTINUE
      Q2NEW=RAD*Q1
      Q3=100.0*Q1/SEN
      TYPE 2210,Q1,Q2NEW,Q3
 2210 FØRMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
      RETURN
      END
```

REFLECTION COIL ABOVE MULTIPLE CONDUCTORS, THICKNESS VARIATION

We shall now consider further the case of a reflection coil above multiple conductors, as shown in Fig. 4 (p. 7). This program calculates the magnitude and phase of the voltage that is fed to the phase measuring circuits of the phase-sensitive eddy-current instrument and is designed to help analyze eddy-current measurements of cladding thickness.

The program calculates the magnitude and phase of the induced voltage for five different values of lift-off with each of three different thickness values of a specific conductor, for a total of fifteen calculations. This allows one to examine the sensitivity to lift-off variations as well as cladding thickness variations. In addition, the program also calculates the phase shift with the discriminator adjusted to give the same phase on the nominal cladding thickness sample with maximum and minimum lift-off. The phase on the nominal sample with minimum lift-off is taken as zero, and all other phase shifts are measured relative to it. The equations which are evaluated are Eq. (8) for the mutual coupling, Eq. (9) for the driver coil impedance, and Eq. (17) for the pickup coil impedance. The gamma factor for the clad conductor is calculated from Eqs. (24) to (26). The programs are written in both BASIC and FORTRAN for use on a PDP-10. The BASIC program follows.

To use this program, one must first divide all coil and lift-off dimensions by the mean radius of the driver coil. Then the following lines must be typed into the program:

```
250     R5 = (numerical value of driver coil mean radius in inches)
260     R1 = (numerical value of normalized driver coil inner radius)
270     R2 = (numerical value of normalized driver coil outer radius)
280     L3 = (numerical value of normalized driver coil length)
290     R3 = (numerical value of normalized pickup coil inner radius)
300     R4 = (numerical value of normalized pickup coil outer radius)
310     L4 = (numerical value of normalized pickup coil length)
320     L5 = (numerical vlaue of normalized pickup recess from face
             of driver)
```

330 L6 = (numerical value of normalized driver coil minimum lift-off)

340 R6 = (numerical value of resistance of driver coil in ohms)

350 R7 = (numerical value of total resistance of both pickup coils in ohms)

360 N3 = (number of turns on driver coil)

370 N4 = (number of turns on each pickup coil)

380 R0 = (output series resistance of driving amplifier in ohms)

390 R9 = (input shunt resistance of pickup amplifier in ohms)

400 C6 = (total shunt capacitance of driving circuit in farads)

410 C7 = (total shunt capacitance of pickup circuit in farads)

420 V0 = (output voltage of driving amplifier in volts)

430 G5 = (gain of pickup amplifier)

440 F = (operating frequency in Hertz)

450 L2 = (numerical value of normalized driver coil lift-off increment)

510 N9 = (total number of conductors + 1)

520 N8 = (number of the specific conductor with thickness variation, refer to Fig. 4)

770 T9 = (numerical value of fractional thickness change of the N8-th layer)

The input data of conductors are typed into the program between the statement numbers 800 and 980, according to the order of appearance from the lowest conductors [refer to Fig. 4 (p. 7)].

```
800     DATA  1E10, K(1), U(1)
810     DATA  T(2), K(2), U(2)
 :        :
 .      DATA  T(N), K(N), U(N)
 :        :
 .      DATA T(N9-1), K(N9-1), U(N9-1)
(980)   DATA  1(arbitrary number), 1E10, 1
```

where

T(N) = numerical value of thickness of the Nth layer conductor in inches,

K(N) = numerical value of resistivity of the Nth layer conductor in microhm centimeters,

U(N) = numerical value of relative permeability of the Nth layer conductor, and

the (N9–1)th layer denotes the top or surface layer.

The current version of MULTIT (BASIC) is limited to a maximum of nine conductors. However, this limitation can be removed easily by adding one DIMENSION statement.

```
60      DIM T(N9), R(N9), U(N9), S(N9), X(N9), Y(N9)
```

The program may now be run. The print-out by the computer will have the following format.

```
N             THICK(INCH)     R(MU-OHM CM)  M,SIGMA       U
(1)           (T(1))          (K(1))        .......       (U(1))
(2)           (T(2))          (K(2))        .......       (U(2))
 :              :               :              :             :
(N9-1)        (T(N9-1))       (K(N9-1))     .......       (U(N9-1))
(N9)          (T(N))          (K(N))        .......       (U(N))
THICKNESS VARIATION OF (N8)-TH LAYER IS + -(100*T9)%
R1= (R1)      R2= (R2)        DRIVER LENGTH IS (L3)
R3= (R3)      R4= (R4)        PICK UP LENGTH IS (L4)
COIL MEAN RADIUS (R5) INCHES     OPERATING FREQUENCY (F)
PICK UP RECESSED (L5)
MINIMUM LIFT-OFF (L6)  LIFT-OFF INCREMENT (L2)
DRIVER RES    INDUCTANCE      NO TURNS      SHUNT CAP     NOR IM PT
  (R6)          ......          (N3)          (C6)          .....
PICKUP RES    INDUCTANCE      NO TURNS      SHUNT CAP     NOR IM PT
  (R7)          ......          (N4)          (C7)          .....
DRIVING VOLT  SERIES RES      AMP GAIN      INPUT IMP
  (V0)          (R0)            (G5)          (R9)
DISCRIMINATOR VOLTAGE IS .....

  (L6)          (L6+L2)         (L6+2L2)      (L6+3L2)      (L6+4L2)

  .....         .....           .....         .....         .....
  .....         .....           .....         .....         .....
  .....         .....           .....         .....         .....

  .....         .....           .....         .....         .....
  .....         .....           .....         .....         .....
   0            .....           .....         .....         .....
```

```
  .....            .....            .....           .....          .....
  .....            .....            .....           .....          .....
  .....            .....            .....           .....          .....
PHASE SHIFT .....  LIFT-OFF .....                  %.....
DEGREE .....                .....
1 COIL DESIGN   2 ATTEN. DESIGN   3 DRIFT CHECK   4 CON CAL
 ?
```

The various symbols enclosed in parentheses are used to indicate that the numerical value of the symbol will be printed.

There are five columns of data, one under each value of lift-off. Each column is divided into three sections of three lines each. These sections correspond, from top to bottom, to the three values of (−100*T9, 0, and +100*T9% variations from nominal) the cladding thickness of the N8-th layer. The three lines in each section are, from top to bottom, the magnitude of the voltage out of the pickup amplifier, the phase shift between the voltage out of the pickup amplifier and the driving voltage, and the phase shift between the voltage out of the pickup amplifier with the discriminator set to give the same phase shift with minimum lift-off and maximum lift-off on the nominal cladding thickness sample. The phase shift in the third line is always measured from the nominal cladding thickness sample with minimum lift-off. The voltage out of the pickup amplifier will be in volts and be either peak-to-peak or RMS, whichever is used for V0, the output voltage of the driving amplifier. For each conductor N, the value of a dimensionless product $R_5{}^2\omega\mu_N\sigma_N$ is also calculated and printed out under the column M,SIGMA. The inductance in henries of the driving coil in air and the normalized imaginary part of the driving coil impedance, with nominal cladding thickness and nominal lift-off (L6+2L2), is also printed. Likewise, the inductance in henries of both pickup coils in air and the normalized imaginary part of the pickup coils' impedance with nominal cladding thickness and lift-off is also printed. The total phase shift for the 200*T9% cladding thickness variation, the maximum phase shift due to lift-off, and the maximum percent of range error in cladding thickness measurements due to lift-off are given. The phase shifts are given first in radians and then in degrees.

The program then enters a branching loop that allows the following options, depending on which of 1, 2, 3, or 4 is typed as input after the question mark.

1. Coil Design

If a 1 is typed by the operator after the question mark, the program will enter the Coil Design Loop. This loop will allow the number of turns on the driver and pickup coils to be varied. The loop will allow the wire gage to be given and then calculate the number of turns and coil resistance, or it will allow the number of turns to be entered and calculate the gage and coil resistance, or both turns and gage can be entered. If zeros are entered for both the gage and turns of either the driver or pickup coils, the present value of these will be retained. The program then starts with the label

DRIVER RES   INDUCTANCE   NO TURNS   SHUNT CAP   NOR IM PT ,

and the remainder of the program is recalculated and printed, with the "new" coil in the circuit. However, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

2. Attenuator Design

This loop will allow the driver series resistance, R0, the driver shunt capacitance, C6, the amplifier input impedance, R9, and the shunt capacitance in the pickup circuit, C7, to be varied. If a 2 is typed after the question mark, the computer will respond with

DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP .

The resistance is to be given in ohms, and the capacitance in farads. If zero is typed in for any value, the present value in the computer will be retained. After the input data and a carriage return are typed, the computer will calculate the ratio of resonant frequency to operating frequency for the particular L-C circuit, a very rough value of resistance for minimum temperature drift, and the ratio between the resistance and reactance in the circuit for both the driver and pickup circuits. The program then starts with the label

DRIVER RES   INDUCTANCE   NO TURNS   SHUNT CAP   NOR IM PT ,

and the remainder of the program is recalculated and printed with the "new" attenuator in the circuit. Again, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

3. Drift Check

This loop calculates the effect of the drift of any of the circuit or sample parameters after the instrument has been calibrated and adjusted. If a 3 is typed as input, the program will respond with the percent variation, the parameter varied, the maximum change in phase (both radians and degrees) of any of the 15 different phases calculated (5 lift-off values for each of 3 different cladding thickness values) and the percent of the range the drift represents. The percent variation of each parameter may be varied independently. The following table gives the parameter, the line number, and the constant to be varied:

Parameter	Line Number	Constant
Driver Resistance	8610	E1
Pickup Resistance	8620	E2
Driver Shunt Cap.	8630	E3
Pickup Shunt Cap.	8640	E4
Series Resistance	8650	E7
Amp. Input Resistance	8660	E8
Applied Voltage	8670	E9
Frequency	8680	A1
Mean Radius	8690	A2

For example, to put in a 2% variation in the driver coil resistance, one would type:

8610 E1 = .02

The amount that each parameter is varied must be set before the program is run. All of the variations are 0.01 or 1% in the current version of the program. Since the phase shift produced by the parameter variation is quite linear over a range of about 10%, a linear interpolation or extrapolation may be used from the 1% parameter variation. If zero is typed in for any parameter variation, that parameter will not be varied nor will it be typed out in the list of parameter variations. When the calculation is completed and the drifts printed, the program returns to the branch point and repeats the question

1 Coil Design 2 Atten. Design 3 Drift Check 4 Con Cal .

The first seven drifts do not require that the numerical integrations to calculate M, Z_{DR}, and Z_{PU} be repeated, but they must be repeated to calculate the drifts due to frequency, mean radius, and resistivity changes of the base and cladding materials. Therefore, the calculation of these last four drifts requires a considerable amount of computer time.

4. Con Cal

This loop is to continue calculations. If a series of calculations is to be made, a loop may be established at this point, However, in the present version of the program, if a 4 is typed as input, the program will end.

Sample Calculation of MULTIT

Let us suppose we wish to design a reflection-type coil to measure the thickness variation of an aluminum cladding with a resistivity of 3.632 μΩ-cm and a nominal thickness of 0.028 in. Below the cladding, there are two conductors, a 0.194 in. layer of aluminum with a resistivity of 5.393 μΩ-cm and a 0.028 in. layer of aluminum with a resistivity of 3.632 μΩ-cm. The driver coil has a mean radius of 0.08325 in., inner and outer radii of 0.0625 and 0.104 in., and a length of 0.030 in. The pickup coils have inner and outer radii of 0.030 and 0.058 in., a length of 0.008 in., and are mounted flush with the ends of the driver coil. The driver coil has 360 turns of No. 46 wire with a resistance of 79.36 Ω, and the pickup coils have 410 turns each of No. 54 wire, with a resistance of 530.5 Ω for both coils. The driver series and the pickup amplifier input resistances are both chosen to be 1 MΩ. The shunt capacitances in both circuits are chosen to be 1 pF. This corresponds to practically infinite source and detector impedances, so that only the mutual coupling, M, affects the phases. The minimum lift-off is taken to be 0.0083 in. with a lift-off increment of 0.002 in. The variation from the nominal thickness of the surface cladding is ±5%. The relative permeability of all layers is 1. The frequency is 10 KHz, the output voltage of the driving amplifier is 10 V, and the gain of the pickup amplifier is unity (a unity gain allows the actual gain needed in the amplifier to be calculated by dividing the maximum output voltage with unity gain into 10).

The program MULTIT is assumed to be in the active core, and the following information is typed into the computer. All linear dimensions are normalized by dividing by the coil mean radius, except for the coil mean radius, which is in inches.

```
250     R5 = .08325
260     R1 = .75
270     R2 = 1.25
280     L3 = .36
290     R3 = .36
300     R4 = .696
310     L4 = .096
320     L5 = 0
330     L6 = .1
340     R6 = 79.36
350     R7 = 530.5
360     N3 = 360
370     N4 = 410
380     R0 = 1E6
390     R9 = 1E6
400     C6 = 1E-12
410     C7 = 1E-12
420     V0 = 10
430     G5 = 1
440     F = 1E4
450     L2 = .025
510     N9 = 5
```

```
520     N8 = 4
770     T9 = .05
800     DATA  1E10, 1E10, 1
810     DATA  .028, 3.632, 1
820     DATA  .194, 5.393, 1
830     DATA  .028, 3.632, 1
840     DATA  1, 1E10, 1
```

The program may now be run with the following results. The data inputed from the terminal by the user are underlined. A carriage return must be typed by the user at the end of each input line.

```
MULTIC(BASIC)

N            THICK(INCH)     R(MU-ØHM CM)   M,SIGMA       U
 1            1.00000E+10    1.00000E+10    0             1
 2            0.028          3.632          9.72034       1
 3            0.194          5.393          6.54632       1
 4            0.028          3.632          9.72034       1
 5            1              1.00000E+10    0             1
CØNDUCTIVITY VARIATIØN ØF 4 TH LAYER IS +--5 %
R1= 0.75      R2= 1.25       DRIVER LENGTH IS 0.36
R3= 0.36      R4= 0.696      PICK UP LENGTH IS 0.096
CØIL MEAN RADIUS 8.32500E-2 INCHES    ØPERATING FREQUENCY 10000
PICK UP RECESSED 0
MIN LIFT-ØFF= 0.1 LIFT-ØFF INCREMENT= 0.025
DRIVER RES    INDUCTANCE     NØ TURNS       SHUNT CAP     NØR IM PT
 79.36         6.05067E-4     360            1.00000E-12   0.849616
PICKUP RES    INDUCTANCE     NØ TURNS       SHUNT CAP     NØR IM PT
 530.5         4.72124E-4     410            1.00000E-12   0.992308
DRIVING VØLT  SERIES RES     AMP GAIN       INPUT IMP
 10            1000000        1              1000000
DISCRIMINATØR VØLTAGE IS-6.34033E-7

 0.1           0.125          0.15           0.175         0.2

 1.28844E-5    1.18250E-5     1.08553E-5     9.96896E-6    9.15943E-6
-0.794269     -0.798561      -0.803418      -0.808744     -0.814461
 1.30444E-2    1.31668E-2     1.31076E-2     1.29845E-2    1.29005E-2

 1.32201E-5    1.21309E-5     1.11340E-5     1.02228E-5    9.39059E-6
-0.806063     -0.810183      -0.814884      -0.820068     -0.825654
 0             1.91204E-4     1.77376E-4     7.85962E-5    0

 1.35424E-5    1.24246E-5     1.14015E-5     1.04664E-5    9.61245E-6
-0.817709     -0.821659      -0.826204      -0.831247     -0.836703
-1.27887E-2   -1.25214E-2    -1.24815E-2    -1.25469E-2   -1.26104E-2
PHASE SHIFT 2.56305E-2 LIFT-ØFF 2.66261E-4 IN % 1.03884
IN DEGREE 1.46852            1.52557E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?1
```

```
DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS
 ?46,0,54,0
DRIVER 391 TURNS ØF # 46 WIRE 17 /LAYER 23 LAYERS 71.9293 ØHM
PICKUP 429 TURNS EA # 54 WIRE 11 /LAYER 39 LAYERS 532.582 ØHMS TØTAL
DRIVER RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 71.9293        7.13760E-4     391            1.00000E-12    0.849616
PICKUP RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 532.582        5.16896E-4     429            1.00000E-12    0.992308
DRIVING VØLT   SERIES RES     AMP GAIN       INPUT IMP
 10             1000000        1              1000000
DISCRIMINATØR VØLTAGE IS-7.20555E-7

 0.1            0.125          0.15           0.175          0.2

 1.46425E-5     1.34385E-5     1.23365E-5     1.13292E-5     1.04092E-5
-0.794277      -0.79857       -0.803426      -0.808752      -0.81447
 1.30444E-2     1.31668E-2     1.31076E-2     1.29845E-2     1.29005E-2

 1.50239E-5     1.37861E-5     1.26532E-5     1.16176E-5     1.06719E-5
-0.806071      -0.810191      -0.814892      -0.820076      -0.825662
 0              1.91189E-4     1.77369E-4     7.85962E-5    -7.45058E-9

 1.53902E-5     1.41199E-5     1.29573E-5     1.18945E-5     1.09241E-5
-0.817717      -0.821667      -0.826213      -0.831255      -0.836711
-1.27886E-2    -1.25214E-2    -1.24815E-2    -1.25469E-2    -1.26104E-2
PHASE SHIFT 2.56305E-2 LIFT-ØFF 2.66239E-4 IN % 1.03876
IN DEGREE 1.46852             1.52544E-2
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?2
```

```
DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP
 ?5.0E2,4.7E-9,6.2E2,4.7E-9
DVR CT 9.42723 BELØW RES 359.202 ØPT RES 13.1225 RES/REACTANCE
P-U CT 10.2505 BELØW RES 330.351 ØPT RES 19.2381 RES/REACTANCE
DRIVER RES     INDUCTANCE     NØ TURNS      SHUNT CAP      NØR IM PT
 71.9293        7.13760E-4     391           4.70000E-9     0.849616
PICKUP RES     INDUCTANCE     NØ TURNS      SHUNT CAP      NØR IM PT
 532.582        5.16896E-4     429           4.70000E-9     0.992308
DRIVING VØLT   SERIES RES     AMP GAIN      INPUT IMP
 10             500            1             620
DISCRIMINATØR VØLTAGE IS-7.81534E-4

 0.1            0.125          0.15          0.175          0.2

 1.37094E-2     1.25929E-2     1.15692E-2    1.06320E-2     9.77486E-3
-0.992003      -0.997071      -1.00265      -1.00864       -1.01498
 1.28689E-2     1.28639E-2     1.27909E-2    1.27662E-2     1.28924E-2

 1.40649E-2     1.29174E-2     1.18652E-2    1.09019E-2     1.00209E-2
-1.00343       -1.00835       -1.0138       -1.01967       -1.0259
 0              2.02060E-5    -4.97103E-5   -9.12398E-5     0

 1.44064E-2     1.32290E-2     1.21494E-2    1.11610E-2     1.02571E-2
-1.01472       -1.0195        -1.02481      -1.03057       -1.03669
-1.26074E-2    -1.25529E-2    -1.26095E-2   -1.26568E-2    -1.25888E-2
PHASE SHIFT 2.54395E-2 LIFT-ØFF 1.26258E-4 IN % 0.496305
IN DEGREE 1.45758             7.23403E-3
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?3

SYSTEM DRIFT VARIATIØNS
% VARIATN      PARAMETER      RADIAN        DEGREE         % ØF RANGE
 1             DRIVER RES     2.72989E-5    1.56411E-3     0.107309
 1             PICKUP RES    -6.51032E-5   -3.73014E-3    -0.255913
 1             DVR SHUNT CAP -2.10963E-4   -1.20873E-2    -0.829273
 1             P-U SHUNT CAP -8.43406E-4   -4.83236E-2    -3.31534
 1             SERIES RES     1.24957E-3    7.15950E-2     4.91191
 1             AMP INPUT RES -6.06865E-4   -3.47708E-2    -2.38552
 1             APPLIED VØLT  -7.94128E-4   -4.55002E-2    -3.12163
 1             FREQUENCY     -6.05208E-3   -0.346759     -23.7901
 1             MEAN RADIUS   -7.63857E-3   -0.437658     -30.0264
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?4
```

The user has exercised all the design options available, and these options may be repeated, omitted, or taken in any order. The BASIC version of the program MULTIT follows.

```
1   REM MULTIT(BASIC)
10 REM REFLECTIØN CØIL FØR THICKNESS VARIATIØN ØF MULTILAYER CØNDUCTØRS
40 DIM A(3,5),B(3,5),C(3,5),D(3,5),E(3,5),F(3,5)
50 DIM M(3,5),P(3,5),Q(3,5)
199 REM CØNSTANT
200 P9=3.14159
210 P8=180/P9
249 REM CØIL DATA
250R5=.08325
260R1=.75
270R2=1.25
280L3=.36
290R3=.36
300R4=.696
310L4=.096
320L5=0
330L6=.1
340R6=79.36
350R7=530.5
360N3=360
370N4=410
379 REM CIRCUIT DATA
380R0=1E6
390R9=1E6
400C6=1E-12
410C7=1E-12
420V0=10.0
430G5=1
440F=10E3
450L2=.025
470L7=L3-2*(L4+L5)
480L8=L7+L4
490L9=L5+2*L6
499 REM CØNDUCTØR DATA
500 DIM K(3),N(3),L(5)
510 N9=5
520 N8=4
529 REM READ T,K,U
530 PRINT "N","THICK(INCH)","R(MU-ØHM CM)","M,SIGMA","U"
535 FØR N=1 TØ N9
537 READ T(N),R(N),U(N)
539 NEXT N
540 GØ SUB 600
550 FØR N=1 TØ N9
560 PRINT N,T(N),R(N),S(N),U(N)
570 NEXT N
580 GØ TØ 750
599 REM SUBRØUTINE FØR M
600 W=2*P9*F
610 FØR N=1 TØ N9
630 S(N)=0
640 IF R(N)>1E9 THEN 660
650 S(N)=.5094*U(N)*F*R5*R5/R(N)
660 NEXT N
670 RETURN
750 T(N9)=0
760 T=T(N8)
770 T9=.05
```

```
780 PRINT "THICKNESS VARIATIØN ØF";N8;"TH LAYER IS +-";100*I9;"%"
799 REM DATA
800 DATA 1E10,1E10,1
810 DATA .028,3.632,1
820 DATA .194,5.393,1
830 DATA .028,3.632,1
840 DATA 1,1E10,1
999 REM PRINT CØIL DATA
1000 PRINT "R1=";R1,"R2=";R2,"DRIVER LENGTH IS";L3
1010 PRINT"R3=";R3,"R4=";R4,"PICK UP LENGTH IS";L4
1020 PRINT "CØIL MEAN RADIUS";R5;"INCHES     ØPERATING FREQUENCY";F
1030 PRINT "PICK UP RECESSED";L5
1040 PRINT "MIN LIFT-ØFF=";L6;"LIFT-ØFF INCREMENT=";L2
1100 REM PRØGRAM BEGINS
1110 REM FØR INTEGRATIØNS
1120 GØ SUB 1500
1130 REM FØR INDUCTANCES AND CIRCUIT; MAGNITUDE AND PHASE
1140 GØ SUB 6000
1150 REM FØR DISCRIMINATØR VØLTAGE AND PHASE SHIFT
1160 GØ SUB 6500
1170 REM FØR PRINTING ØF RESULTS
1180 GØ SUB 6700
1190 REM FØR AV. PHASE SHIFT AND LIFT-ØFF ERRØR
1200 GØ SUB 7000
1400 REM FØR CØIL AND ATTENUATØR DESIGNS, AND DRIFT
1410 GØ TØ 7200
1499 REM SUBRØUTINE FØR INTEGRATIØN
1500 A3=0
1510 A4=0
1520 FØR I=1 TØ 3
1530 FØR J=1 TØ 5
1540 A(I,J)=0
1550 B(I,J)=0
1560 C(I,J)=0
1570 D(I,J)=0
1580 E(I,J)=0
1590 F(I,J)=0
1600 NEXT J
1610 NEXT I
1620 LET S2=5
1630 B1=0
1640 B2=5
1650 S1=1E-2
1660 FØR X=B1+S1/2 TØ B2 STEP S1
1670 GØ SUB 2000
1680 NEXT X
1690 B1=B2
1700 B2=B2+S2
1710 S1=.05
1720 IF X<9 THEN 1660
1730 S1=.1
1740 IF X<29 THEN 1660
1750 S1=.2
1760 IF X<39 THEN 1660
1770 S1=.5
1780 IF X<79 THEN 1660
1790 RETURN
1998 REM SUBRØUTINE FØR L-FACTØR AND INTEGRANTS
```

```
1999 REM FØR J-FACTØR
2000 GØ SUB 2700
2010 W5=0
2020 W2=0
2030 W6=0
2040 W7=0
2050 W4=1
2060 W8=1
2070 W3=1
2080 IF X*L5>20 THEN 2100
2090 W5=EXP(-X*L5)
2100 IF X*L2>20 THEN 2120
2110 W2=EXP(-X*L2)
2120 IF X*L6>20 THEN 2140
2130 W6=EXP(-X*L6)
2140 IF X*L7>20 THEN 2160
2150 W7=EXP(-X*L7)
2160 IF X*L4>15 THEN 2220
2170 W4=1-EXP(-X*L4)
2180 IF X*L8>15 THEN 2220
2190 W8=1-EXP(-X*L8)
2200 IF X*L3>15 THEN 2220
2210 W3=1-EXP(-X*L3)
2220 IF X>30 THEN 2460
2230 IF X*L9>20 THEN 2460
2240 A5=W6*W6*W3*W4*W5*W8*S3
2250 A6=W6*W6*W3*W3*S4
2260 A7=W6*W6*W4*W4*W5*W5*W8*W8*S5
2270 L(1)=1
2280 FØR J=2 TØ 5
2290 L(J)=0
2300 IF J*X*L2>20 THEN 2320
2310 L(J)=W2*L(J-1)
2320 NEXT J
2329 REM FØR GAMMA FACTØR
2330 GØ SUB 3200
2340 FØR I=1 TØ 3
2350 FØR J=1 TØ 5
2360 Q1=K(I)*L(J)*L(J)
2370 Q2=-N(I)*L(J)*L(J)
2380 A(I,J)=A(I,J)+Q2*A5
2390 B(I,J)=B(I,J)+Q1*A5
2400 C(I,J)=C(I,J)+Q2*A6
2410 D(I,J)=D(I,J)+Q1*A6
2420 E(I,J)=E(I,J)+Q2*A7
2430 F(I,J)=F(I,J)+Q1*A7
2440 NEXT J
2450 NEXT I
2460 A3=A3+2*(X*L3-W3)*S4
2470 A4=A4+(4*(X*L4-W4)-2*W7*W4*W4)*S5
2480 RETURN
2699 REM SUBRØUTINE FØR J5=J(R1,R2)/X↑3,J6=J(R3,R4)/X↑3
2700 R=R1
2710 GØ SUB 2900
2720 J1=Q2
2730 R=R2
2740 GØ SUB 2900
2750 J5=Q2-J1
```

```
2760 R=R3
2770 GØ SUB 2900
2780 J3=Q2
2790 R=R4
2800 GØ SUB 2900
2810 J6=Q2-J3
2820 S3=S1*J5*J6
2830 S4=S1*J5*J5
2840 S5=S1*J6*J6
2850 RETURN
2899 REM SUBRØUTINE FØR Q2=J(R,O)*X↑3
2900 Z=X*R
2910 IF Z>5 THEN 3000
2920 Q1=R*R*R/2
2930 Q2=Q1/3
2940 Q3=INT(2*Z)+3
2950 FØR Q=1 TØ Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 GØ TØ 3050
3000 Q1=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
3010 Q1=((Q1-0.1730503)/Z+0.7034845)/Z-0.064109E-3
3020 Q2=(((-5.817517/Z+2.105874)/Z-0.6896196)/Z+0.4952024)/Z
3030 Q2=(Q2-0.187344E-2)/Z+0.7979095
3040 Q2=(1-SQR(Z)*(Q2*CØS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3198 REM SUBRØUTINE FØR GAMMA FACTØR(K(I),N(I))
3199 REM FØR BETA(X1,Y1)N
3200 Q1=X*X
3210 Q2=Q1*Q1
3220 Q=0
3230 N=N9
3240 M1=S(N)
3250 U1=U(N)
3260 GØ SUB 5000
3270 X(N)=X1
3280 Y(N)=Y1
3290 Q=Q+X1*T(N)/R5
3300 IF Q>20 THEN 3340
3310 IF N=1 THEN 3340
3320 N=N-1
3330 GØ TØ 3240
3340 N7=N
3350 REM FØR GAMMA FACTØR
3360 N=N7+1
3370 GØ SUB 5100
3380 GØ SUB 5150
3390 IF N8=N7+1 THEN 3560
3400 XO=X(N7+1)
3410 YO=Y(N7+1)
3420 REM FØR V(M,N7)J,2
3430 N6=N8
3440 IF N8>N7+1 THEN 3470
3450 REM FØR V(K,N7)J,2
3460 N6=N9
3470 FØR N=N7+2 TØ N6
3480 X1=X(N)
```

```
3490 Y1=Y(N)
3500 GØ SUB 5300
3510 GØ SUB 5580
3520 X0=X1
3530 Y0=Y1
3540 NEXT N
3550 IF N8<N7+1 THEN 3970
3560 I1=V3
3570 I2=V4
3580 I3=V7
3590 I4=V8
3600 IF N8=N9-1 THEN 3920
3610 REM FØR V(K,M+1)L,I
3620 X0=X(N8+1)
3630 Y0=Y(N8+1)
3640 N=N8+2
3650 X1=X(N)
3660 Y1=Y(N)
3670 GØ SUB 5300
3680 V1=T1
3690 V2=T2
3700 V3=T3
3710 V4=T4
3720 V5=T5
3730 V6=T6
3740 V7=T7
3750 V8=T8
3760 IF N8=N9-2 THEN 3870
3770 X0=X(N8+2)
3780 Y0=Y(N8+2)
3790 FØR N=N8+3 TØ N9
3800 X1=X(N)
3810 Y1=Y(N)
3820 GØ SUB 5300
3830 GØ SUB 5500
3840 X0=X1
3850 Y0=Y1
3860 NEXT N
3870 I5=V3
3880 I6=V4
3890 I7=V7
3900 I8=V8
3910 REM FØR T(M+1,M)I,J
3920 X0=X(N8)
3930 Y0=Y(N8)
3940 N=N8+1
3950 X1=X(N)
3960 Y1=Y(N)
3970 FØR I=1 TØ 3
3980 IF N8<N7+1 THEN 4190
3990 T(N-1)=T*(1+(I-2)*T9)
4000 GØ SUB 5300
4010 REM FØR T(M+1,M)I,J V(M,1)J,2
4020 V3=I1
4030 V4=I2
4040 V7=I3
4050 V8=I4
4060 GØ SUB 5580
```

```
4070 IF N8=N9-1 THEN 4190
4080 REM FØR V(K,M+1)L,I .....
4090 T1=V1
4100 T2=V2
4110 T3=I5
4120 T4=I6
4130 T5=V5
4140 T6=V6
4150 T7=I7
4160 T8=I8
4170 GØ SUB 5580
4180 REM FØR GAMMA FACTØR
4190 V9=V7/V8+V8/V7
4200 K(I)=(V3/V8+V4/V7)/V9
4210 N(I)=(V4/V8-V3/V7)/V9
4220 NEXT I
4230 RETURN
4999 REM SUBRØUTINE FØR BETA(X1,Y1)
5000 IF M1<Q1*1E-5 THEN 5050
5010 Q3=SQR(Q2+M1*M1)
5020 X1=.707106781*SQR(Q3+Q1)/U1
5030 Y1=.707106781*SQR(Q3-Q1)/U1
5040 GØ TØ 5070
5050 X1=X/U1
5060 Y1=0
5070 RETURN
5099 REM SUBRØUTINE FØR INITIAL STEPS
5100 X0=X(N-1)
5110 Y0=Y(N-1)
5120 X1=X(N)
5130 Y1=Y(N)
5140 RETURN
5150 V3=X1-X0
5160 V4=Y1-Y0
5170 V7=X1+X0
5180 V8=Y1+Y0
5190 RETURN
5299 REM SUBRØUTINE FØR XFØRMATIØM MATRIX T
5300 Q2=X1+X0
5310 Q1=X1-X0
5320 Q4=Y1+Y0
5330 Q3=Y1-Y0
5340 Q5=U(N-1)*T(N-1)/R5
5350 Q6=EXP(Q5*X0)
5360 Q7=CØS(Q5*Y0)
5370 Q8=SIN(Q5*Y0)
5380 T1=(Q2*Q7+Q4*Q8)/Q6
5390 T2=(Q4*Q7-Q2*Q8)/Q6
5400 T3=(Q1*Q7-Q3*Q8)*Q6
5410 T4=(Q3*Q7+Q1*Q8)*Q6
5420 T5=(Q1*Q7+Q3*Q8)/Q6
5430 T6=(Q3*Q7-Q1*Q8)/Q6
5440 T7=(Q2*Q7-Q4*Q8)*Q6
5450 T8=(Q4*Q7+Q2*Q8)*Q6
5460 RETURN
5499 REM SUBRØUTINE FØR XFØRMATIØN MATRIX V
5500Q1=V1
5510Q2=V2
```

```
5520Q5=V5
5530Q6=V6
5540 V1=T1*Q1-T2*Q2+T3*Q5-T4*Q6
5550 V2=T2*Q1+T1*Q2+T4*Q5+T3*Q6
5560 V5=T5*Q1-T6*Q2+T7*Q5-T8*Q6
5570 V6=T6*Q1+T5*Q2+T8*Q5+T7*Q6
5580Q3=V3
5590Q4=V4
5600Q7=V7
5610Q8=V8
5620 V3=T1*Q3-T2*Q4+T3*Q7-T4*Q8
5630 V4=T2*Q3+T1*Q4+T4*Q7+T3*Q8
5640 V7=T5*Q3-T6*Q4+T7*Q7-T8*Q8
5650 V8=T6*Q3+T5*Q4+T8*Q7+T7*Q8
5660 RETURN
5999 REM SUBRØUTINE FØR CIRCUIT, MAGNITUDE, AND PHASE
6000N1=N3/((R2-R1)*L3)
6010N2=N4/((R4-R3)*L4)
6020Q0=6.300475204E-7*F*R5
6030 W1=W*C6*R0
6040 W2=W*C7*R9
6050 W3=1-W1*W2
6060 W4=W1+W2
6070 FØR I=1 TØ 3
6080 FØR J=1 TØ 5
6090Z8=Q0*N1*N2*A(I,J)
6100Z9=Q0*N1*N2*B(I,J)
6110Z=Q0*N1*N1*C(I,J)
6120Z2=Q0*N1*N1*(D(I,J)+A3)
6130Z1=Q0*N2*N2*E(I,J)
6140Z3=Q0*N2*N2*(F(I,J)+A4)
6150 Q1=R0+R6+Z-W1*Z2
6160 Q2=R9+R7+Z1-W2*Z3
6170 Q3=Z2+W1*(R6+Z)
6180 Q4=Z3+W2*(R7+Z1)
6190 Q5=Z8*Z8-Z9*Z9
6200 Q6=2*Z8*Z9
6210 Q7=Q1*Q2-Q3*Q4-(W3*Q5-W4*Q6)
6220 Q8=Q1*Q4+Q3*Q2-(W4*Q5+W3*Q6)
6230 Q9=Z8*Q7+Z9*Q8
6240 W5=Z9*Q7-Z8*Q8
6250 M(I,J)=G5*R9*V0*SQR(Q9*Q9+W5*W5)/(Q7*Q7+Q8*Q8)
6260 P(I,J)=ATN(W5/Q9)
6270 IF Q9>0 THEN 6290
6280 P(I,J)=P(I,J)+SGN(W5)*P9
6290 NEXT J
6300 NEXT I
6310 RETURN
6499 REM SUBRØUTINE FØR DISC. VØLTAGE AN PHASE SHIFT
6500 Q1=M(2,5)*SIN(P(2,5))-M(2,1)*SIN(P(2,1))
6510 Q2=-M(2,5)*CØS(P(2,5))+M(2,1)*CØS(P(2,1))
6520 Q3=ATN(Q1/Q2)
6530 IF Q2>0 THEN 6550
6540 Q3=Q3+SGN(Q1)*P9
6550 V1=M(2,1)*SIN(Q3+P(2,1))
6555 Ø1=Q3
6556 Ø2=V1
6560 FØR I=1 TØ 3
```

```
6570 FØR J=1 TØ 5
6580 Q(I,J)=Q3-ATN(V1/SQR(M(I,J)*M(I,J)-V1*V1))+P(I,J)
6590 NEXT J
6600 NEXT I
6610 RETURN
6699 REM SUBRØUTINE FØR PRINTING RESULTS
6700PRINT"DRIVER RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6710PRINTR6,Q0*N1*N1*A3/W,N3,C6,(D(2,3)+A3)/A3
6720PRINT"PICKUP RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6730PRINTR7,Q0*N2*N2*A4/W,N4,C7,(F(2,3)+A4)/A4
6740PRINT "DRIVING VØLT","SERIES RES","AMP GAIN","INPUT IMP"
6750PRINTV0,R0,G5,R9
6760PRINT "DISCRIMINATØR VØLTAGE IS";V1
6770 PRINT
6780 PRINT L6,L6+L2,L6+2*L2,L6+3*L2,L6+4*L2
6790 FØR I=1 TØ 3
6800 PRINT
6810 PRINT M(I,1),M(I,2),M(I,3),M(I,4),M(I,5)
6820 PRINT P(I,1),P(I,2),P(I,3),P(I,4),P(I,5)
6830 PRINT Q(I,1),Q(I,2),Q(I,3),Q(I,4),Q(I,5)
6840 NEXT I
6850 RETURN
6999 REM SUBRØUTINE FØR AV. PHASE SHIFT AND LIFT-ØFF ERRØR
7000 Q1=Q(1,1)
7010 Q2=Q(1,1)
7020 FØR J=2 TØ 5
7030 IF Q(1,J)<Q1 THEN 7050
7040 Q1=Q(1,J)
7050 IF Q(1,J)>Q2 THEN 7070
7060 Q2=Q(1,J)
7070 NEXT J
7080 Q=(Q(1,1)+Q(1,2)+Q(1,3)+Q(1,4)+Q(1,5))/5
7090 Q=Q-(Q(3,1)+Q(3,2)+Q(3,3)+Q(3,4)+Q(3,5))/5
7092 Ø=Q
7100 PRINT"PHASE SHIFT";Q;"LIFT-ØFF";Q1-Q2;"IN %";100*(Q1-Q2)/Q
7110 PRINT"IN DEGREE";Q*P8,(Q1-Q2)*P8
7120 RETURN
7199 REM FØR CØIL DESIGN, ATTENUATØR, DRIFT, AND EXIT
7200PRINT"1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL"
7210INPUT N5
7220PRINT
7230ØN N5 GØ TØ 7300,8200,8600,9900
7299 REM FØR CØIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FØR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 GØ SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER";N3;"TURNS ØF #";G;"WIRE";
7390 PRINT Q7;"/LAYER";Q8;"LAYERS";R6;"ØHM"
7399 REM FØR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
```

```
7430 W2=R4
7440 W3=L4
7450 GØ SUB 7510
7460 N4=Q2
7470 R7=2*Q9
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIRE";
7490 PRINT Q7;"/LAYER";Q8;"LAYERS";R7;"ØHMS TØTAL"
7500 GØ TØ 1140
7509 REM SUBRØUTINE FØR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FØR GAGE
7540 G=Q1
7550 IF G>.5 THEN 7640
7560 Q5=.95*SQR((W2-W1)*W3/Q2)
7570 Q6=1.0371E-5/Q5/Q5
7580 G0=40
7590 G=40+10*(LØG(Q6)-LØG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 GØ TØ 7590
7630 G=INT(G)
7639 REM FØR TURN NUMBER AND R6
7640 Q6=(.9989+.017*(G/10-1))*10↑(G/10-4)
7650 Q5=SQR(1.0371E-5/Q6)
7660 IF G> 40 THEN 7690
7670 Q5=(.460655*LØG(Q5*1E3)-.43444)*1E-3+Q5
7680 GØ TØ 7700
7690 Q5=(98.02228*Q5+2.56791E-2)*1E-3+Q5
7700 Q7=INT(W3/Q5)
7710 Q8=INT((W2-W1)/Q5)
7720 IF Q2>.5 THEN 7740
7730 Q2=Q7*Q8
7740 Q9=Q2*Q6*(W2+W1)*P9/12
7750 RETURN
8199 REM FØR ATTENUATØR DESIGN
8200 PRINT "DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP"
8210 INPUT Q1,Q2,Q3,Q4
8220 IF Q1=0 THEN 8240
8230 R0=Q1
8240 IF Q2=0 THEN 8260
8250 C6=Q2
8260 IF Q3=0 THEN 8280
8270 R9=Q3
8280 IF Q4=0 THEN 8300
8290 C7=Q4
8300 Q1=Q0*N1*N1*(D(2,3)+A3)/W
8310 Q2=Q0*N2*N2*(F(2,3)+A4)/W
8320 PRINT "DVR CT";1/(W*SQR(Q1*C6));"BELØW RES";
8330 PRINT SQR(Q1/C6);"ØPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELØW RES";
8350 PRINT SQR(Q2/C7);"ØPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 GØ TØ 1140
8599 REM FØR DRIFTS
8600 PRINT"SYSTEM DRIFT VARIATIØNS"
8610 E1=.01
8620 E2=.01
```

```
8630 E3=.01
8640 E4=.01
8650 E7=.01
8660 E8=.01
8670 E9=.01
8680 A1=.01
8690 A2=.01
8710 PRINT "% VARIATN","PARAMETER","RADIAN","DEGREE","% ØF RANGE"
8720 IF E1=0 THEN 8770
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 GØ SUB 9320
8760 R6=R6/(1+E1)
8770 IF E2=0 THEN 8820
8780 R7=R7*(1+E2)
8790 PRINT 100*E2,"PICKUP RES",
8800 GØ SUB 9320
8810 R7=R7/(1+E2)
8820 IF E3=0 THEN 8870
8830 C6=C6*(1+E3)
8840 PRINT 100*E3,"DVR SHUNT CAP",
8850 GØ SUB 9320
8860 C6=C6/(1+E3)
8870 IF E4=0 THEN 8920
8880 C7=C7*(1+E4)
8890 PRINT 100*E4,"P-U SHUNT CAP",
8900 GØ SUB 9320
8910 C7=C7/(1+E4)
8920 IF E7=0 THEN 8970
8930 R0=R0*(1+E7)
8940 PRINT 100*E7,"SERIES RES",
8950 GØ SUB 9320
8960 R0=R0/(1+E7)
8970 IF E8=0 THEN 9020
8980 R9=R9*(1+E8)
8990 PRINT 100*E8,"AMP INPUT RES",
9000 GØ SUB 9320
9010 R9=R9/(1+E8)
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VØLT",
9050 GØ SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 GØ SUB 9300
9110 F=F/(1+A1)
9120 IF A2=0 THEN 9170
9130 R5=R5*(1+A2)
9140 PRINT 100*A2,"MEAN RADIUS",
9150 GØ SUB 9300
9160 R5=R5/(1+A2)
9170 GØ TØ 7200
9299 REM SUBRØUTINE FØR DRIFT
9300 GØ SUB 600
9310 GØ SUB 1500
9320 GØ SUB 6000
```

```
9330 Q1=0
9340 FØR I=1 TØ3
9350 FØR J=1 TØ 5
9360 Q2=Q1-ATN(Q2/SQR(M(I,J)*M(I,J)-Q2*Q2))+P(I,J)-Q(I,J)
9370 IF ABS(Q1)>ABS(Q2) THEN 9390
9380 Q1=Q2
9390 NEXT J
9400 NEXT I
9410 PRINT Q1,180*Q1/P9,100*Q1/Q
9420 RETURN
9900 END
```

MULTIT, FORTRAN Version

The FORTRAN version of MULTIT is very similar to the BASIC version. The line numbers given are only for identification and editing purposes and have no effect on the actual execution of the FORTRAN program. The data must be typed in the seventh column, or six spaces must first be typed. The data are inputed as follows:

00250 R5 = (coil mean radius in inches)
00260 R1 = (normalized inner radius of driver coil)
00270 R2 = (normalized outer radius of driver coil)
00280 L3 = (normalized length of driver coil)
00290 R3 = (normalized inner radius of pickup coil)
00300 R4 = (normalized outer radius of pickup coil)
00310 L4 = (normalized length of pickup coil)
00320 L5 = (normalized length of recess of each pickup coil from the face of the driver coil)
00330 L6 = (normalized minimum lift-off of the driver coil)
00340 R6 = (resistance of driver coil in ohms)
00350 R7 = (resistance of both pickup coils in ohms)
00360 N3 = (number of turns on the driver coil)
00370 N4 = (number of turns on each pickup coil)
00380 R0 = (driver amplifier series resistance in ohms)
00390 R9 = (pickup amplifier shunt resistance in ohms)
00400 C6 = (shunt capacitance of driver circuit in farads)
00410 C7 = (shunt capacitance of pickup circuit in farads)
00420 V0 = (output voltage in volts)
00430 G5 = (amplifier gain)
00440 F = (operating frequency in Hertz)
00450 L2 = (normalized lift-off increment of the driver coil)
00510 N9 = (total number of conductors + 1)
00520 N8 = (number of the specific conductor with conductivity variation)

```
00540      DATA  RHO/(resistivities in microhm-cm)/
00550      DATA  U/(permeabilities)/
00560      DATA  T/(thicknesses in inches)/
00740      T9 = (fractional variation of thickness of the N8-th layer)
```

The current version of MULTIT.F4 is limited to a maximum of nine conductors. However, this limitation can be removed easily by changing one DIMENSION statement.

```
00110      DIMENSION  T(N9), U(N9), RHO(N9), M(N9), BETA(N9) .
```

The print-out of the FORTRAN version of MULTIT is practically identical to the BASIC version and will not be repeated. The main difference is that the question mark is not printed out when the program is ready to accept data. The Coil Design, Attenuator Design, Drift Check, and Continue Calculations options are the same. The line numbers constant names, and parameter varied in the drift calculations are as follows:

Line Number	Constant	Parameter Varied
04230	DR1	Driver Resistance
04240	DR2	Pickup Resistance
04250	DR3	Driver Shunt Capacitance
04260	DR4	Pickup Shunt Capacitance
04270	DR5	Series Resistance
04280	DR6	Amplifier Input Resistance
04290	DR7	Applied Voltage
04300	DR8	Frequency
04310	DR9	Mean Radius

For example, to vary the driver resistance by 2% one would type:

```
04230      DR1 = 0.02
```

As in the BASIC version, the last two drifts require that the entire numerical integration be repeated and are relatively long running. If any of the drifts is set equal to zero, it will be omitted from the drift calculations.

Sample Calculation of MULTIT.F4

Let us suppose that we wish to design a reflection type coil, identical to the one designed by the BASIC version. We will put the following data in the program (generally by using the EDIT MULTIC.F4 command on the PDP-10 and inserting the statements). All linear dimensions are normalized by dividing by the coil mean radius, except the coil mean radius, which is in inches.

```
00250        R5 = .08325
00260        R1 = 0.75
00270        R2 = 1.25
00280        L3 = .36
00290        R3 = .36
00300        R4 = .696
00310        L4 = .096
00320        L5 = 0.0
00330        L6 = 0.1
00340        R6 = 79.36
00350        R7 = 530.5
00360        N3 = 360.
00370        N4 = 410.
00380        R0 = 1.E6
00390        R9 = 1.E6
00400        C6 = 1.E-12
00410        C7 = 1.E-12
00420        V0 = 10.0
00430        G5 = 1.0
00440        F = 1.0E4
00450        L2 = 0.025
00510        N9 = 5
00520        N8 = 4
```

```
00540       DATA  RHO/1.E10, 3.632, 5.393, 3.632, 1.E10, 5*0./
00550       DATA  U/5*1., 5*0./
00560       DATA  T/1.E10, 2.8E-2, 1.94E-1, 2.8E-2, 1., 5*0./
00740       T9 = 0.05
```

The FORTRAN program may now be executed. The print-out will be essentially identical to the BASIC print-out and will not be repeated. The FORTRAN version of MULTIT follows.

```
C      THIS PRØGRAM EVALUATES THE SENSITIVITY TØ A THICKNESS
C      VARIATIØN IN ANY GIVEN LAYER ØF A MULTI-LAYERED
C      MATERIAL
       CØMPLEX BETA0,BETA1,BETA,V,V97,TR,GAMMA,MUT,DRIVER
       CØMPLEX PICKUP
       CØMMØN X,Z,01,PI/B1/BETA0,BETA1
       CØMMØN /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
       CØMMØN /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
       CØMMØN /B3/PICKUP,AIR1,AIR2/B4/GAGE,XIN,XØUT
       CØMMØN /B4/XLEN,TURNS,N1A,J1,PERLAY,XLAY
       DIMENSIØN T(10),U(10),RHØ(10),M(10),BETA(10)
       DIMENSIØN V(2,2),V97(2,2),TR(2,2),GAMMA(3),DRIVER(3,5)
       DIMENSIØN PICKUP(3,5),RL(5),TMAG(3,5),PHASE(3,5)
       DIMENSIØN SHIFT(3,5),MUT(3,5)
       REAL L2,L3,L4,L5,L6,L7,M,N3,N4
       PI=3.1415926536
       RAD=180.0/PI
C
C
C
C
       JKL=0
C      THE FØLLØWING ARE INPUT DATA FØR THE PARAMETERS ØF
C      THE CØILS,MATERIAL,AND CIRCUIT
       R5=0.08325
       R1=0.75
       R2=1.25
       L3=0.36
       R3=.36
       R4=.696
       L4=.096
       L5=0.0
       L6=0.1
       R6=79.36
       R7=530.5
       N3=360.0
       N4=410.0
       R0=1.0E6
       R9=1.0E6
       C6=1.0E-12
       C7=1.0E-12
       V0=10.0
       G5=1.0
       F=1.0E4
       L2=0.025
C      N9 IS THE TØTAL NUMBER ØF LAYERS,INCLUDING THE CØIL
C      ZØNE,AND N8 IS THE LAYER WHØSE THICKNESS VARIES
C
C
C
       N9=5
       N8=4
       IF(N9.LT.3.ØR.N8.GE.N9.ØR.N8.EQ.1) GØ TØ 1010
       DATA RHØ/1.E10,3.632,5.393,3.632,1.E10,5*0.0/
       DATA U/5*1.0,5*0.0/
       DATA T/1.E10,.028,.194,.028,1.,5*0.0/
       L7=L3-2.0*(L4+L5)
     5 W=2.0*PI*F
```

```
      IF(JKL.NE.0) GØ TØ 15
      TYPE 10
   10 FØRMAT(1H ,1HN,13X,10HTHICK.(IN),4X,11HR(M-ØHM CM),
     13X,7HM,SIGMA,7X,1HU)
   15 DØ 50 I=1,N9
      IF(RHØ(I).GT.1.0E9) GØ TØ 20
      M(I)=0.5094*U(I)*F*R5*R5/RHØ(I)
      GØ TØ 25
   20 M(I)=0.0
   25 IF(JKL.NE.0) GØ TØ 50
   30 TYPE 40,I,T(I),RHØ(I),M(I),U(I)
   40 FØRMAT(1H ,I2,12X,1PE12.5,2X,E12.5,2X,E12.5,2X,0PF6.2)
   50 CØNTINUE
      T(N9)=0.0
      T0=T(N8)
      T9=0.05
      IF(JKL.NE.0) GØ TØ 105
      TVAR=100.0*T9
C     THE SYSTEM PARAMETERS ARE PRINTED ØUT
      TYPE 55,N8,TVAR
   55 FØRMAT(1H ,22HTHICKNESS VARIATIØN ØF,I3,14HTH LAYER
     1 IS +-,F6.2,1H%)
      TYPE 470
      TYPE 60,R1,R2,L3
   60 FØRMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
     1F8.5)
      TYPE 70,R3,R4,L4
   70 FØRMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
     1F8.5)
      TYPE 80,R5,F
   80 FØRMAT(1H ,17HCØIL MEAN RADIUS=,F8.5,7H INCHES,3X,
     120HØPERATING FREQUENCY=,1PE12.5)
      TYPE 90,L5
   90 FØRMAT(1H ,15HPICKUP RECESSED,F8.5)
      TYPE 100,L6,L2
  100 FØRMAT(1H ,13HMIN LIFT-ØFF=,F8.5,3X,19HLIFT-ØFF INCREM
     1ENT=,F8.5)
C     THE INTEGRATIØN BEGINS HERE. THE MUTUAL,DRIVER,AND
C     PICKUP INDUCTANCES AND THE AIR VALUES ARE CALCULATED
  105 S1=0.01
      S2=5.0
      B1=0.0
      B2=S2
      DØ 107 I=1,3
      DØ 107 J=1,5
      MUT(I,J)=(0.0,0.0)
      DRIVER(I,J)=(0.0,0.0)
  107 PICKUP(I,J)=(0.0,0.0)
      AIR1=0.0
      AIR2=0.0
  110 I1=(B2-B1)/S1
      X=B1-S1/2.0
      DØ 390 IDX=1,I1
      X=X+S1
      TEST=X*L3
      IF(TEST.GT.20.0) GØ TØ 120
      W3=EXP(-TEST)
```

```
      GØ TØ 130
  120 W3=0.0
  130 W8=1.0-W3
      TEST=X*L4
      IF(TEST.GT.20.0) GØ TØ 140
      W4=EXP(-TEST)
      GØ TØ 150
  140 W4=0.0
  150 W9=1.0-W4
      TEST=X*L7
      IF(TEST.GT.20.0) GØ TØ 160
      W7=EXP(-TEST)
      GØ TØ 170
  160 W7=0.0
  170 W5=EXP(-X*L5)
      W0=1.0-W7*W4
      TEST=X*L6
      IF(TEST.GT.20.0) GØ TØ 385
      W6=EXP(-2.0*TEST)
      Z=X*R2
      Q1=R2
C     SUBRØUTINE BESSEL EVALUATES THE INTEGRAL ØF XJ1(X)
      CALL BESSEL(VAL2)
      Z=X*R1
      Q1=R1
      CALL BESSEL(VAL1)
      Z=X*R4
      Q1=R4
      CALL BESSEL(VAL4)
      Z=X*R3
      Q1=R3
      CALL BESSEL(VAL3)
      S3=S1*(VAL2-VAL1)*(VAL4-VAL3)
      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
      A5=W6*W5*W8*W9*W0*S3
      A6=W6*W8*W8*S4
      A7=W6*W5*W5*W9*W9*W0*W0*S5
      IF(X.GT.30.0) GØ TØ 385
C     THE LØWEST SIGNIFICANT LAYER,N7,IS DETERMINED
      QSUM=0.0
      N=N9
      TEST=X*X*1.0E-5
  180 IF(M(N).LT.TEST) GØ TØ 190
      BETA(N)=CSQRT(CMPLX(X*X,M(N)))/U(N)
      GØ TØ 200
  190 BETA(N)=CMPLX(X,0.0)
  200 QSUM=QSUM+REAL(BETA(N))*T(N)/R5
      IF(QSUM.GT.20.0.ØR.N.EQ.1) GØ TØ 210
      N=N-1
      GØ TØ 180
  210 N7=N
C     THE MATRIX ELEMENTS V(N7+1,N7)L,2 (L=1,2) ARE
C     CALCULATED
      V(1,2)=BETA(N+1)-BETA(N)
      V(2,2)=BETA(N+1)+BETA(N)
C     THE TØTAL MATRIX V(N9,N7) IS CALCULATED BETWEEN HERE
```

```
C     AND LINE 330. THE GAMMA FACTØR IS JUST THE RATIØ
C     V(N9,N7)1,2/V(N9,N7)2,2. SUBRØUTINE XFØRM CALCULATES
C     THE TRANSFØRMATIØN MATRIX T(M+1,M)I,J AND SUBRØUTINE
C     MATRIX THEN CALCULATES V(K,L)I,J
      IF(N8.EQ.(N7+1)) GØ TØ 260
      BETA0=BETA(N7+1)
      N6=N8
      IF(N8.GT.(N7+1)) GØ TØ 240
      N6=N9
  240 IDX1=N7+2
      IF(IDX1.GT.N6) GØ TØ 255
      DØ 250 N=IDX1,N6
      BETA1=BETA(N)
      CALL XFØRM(N,TR,R5,U,T)
      JUMP=1
      CALL MATRIX(JUMP,V,TR)
  250 BETA0=BETA1
  255 IF(N8.LT.(N7+1)) GØ TØ 310
  260 V97(1,2)=V(1,2)
      V97(2,2)=V(2,2)
      IF(N8.EQ.(N9-1)) GØ TØ 300
      N=N8+2
      BETA0=BETA(N8+1)
      BETA1=BETA(N)
      CALL XFØRM(N,TR,R5,U,T)
      DØ 270 I=1,2
      DØ 270 J=1,2
  270 V(I,J)=TR(I,J)
      IF(N8.EQ.(N9-2)) GØ TØ 290
      BETA0=BETA(N8+2)
      IDX1=N8+3
      IF(IDX1.GT.N9) GØ TØ 290
      DØ 280 N=IDX1,N9
      BETA1=BETA(N)
      CALL XFØRM(N,TR,R5,U,T)
      JUMP=0
      CALL MATRIX(JUMP,V,TR)
  280 BETA0=BETA1
  290 V97(1,1)=V(1,2)
      V97(2,1)=V(2,2)
  300 N=N8+1
      BETA0=BETA(N8)
      BETA1=BETA(N)
  310 DØ 330 I=1,3
      IF(N8.LT.(N7+1)) GØ TØ 330
      AI=I
      T(N-1)=T0*(1.0+(AI-2.0)*T9)
      CALL XFØRM(N,TR,R5,U,T)
      V(1,2)=V97(1,2)
      V(2,2)=V97(2,2)
      JUMP=1
      CALL MATRIX(JUMP,V,TR)
      IF(N8.EQ.(N9-1)) GØ TØ 330
      DØ 320 J=1,2
      TR(J,1)=V(J,1)
  320 TR(J,2)=V97(J,1)
      JUMP=1
      CALL MATRIX(JUMP,V,TR)
```

```
  330 GAMMA(I)=V(1,2)/V(2,2)
      T(N8)=T0
      RL(1)=1.0
      TEST=X*L2
      IF(TEST.GT.20.0) GØ TØ 340
      W2=EXP(-2.0*TEST)
      GØ TØ 350
  340 W2=0.0
  350 DØ 370 K=2,5
      AK=K
      TEST=AK*X*L2
      IF(TEST.GT.20.0) GØ TØ 360
      RL(K)=W2*RL(K-1)
      GØ TØ 370
  360 RL(K)=0.0
  370 CØNTINUE
      DØ 380 J=1,3
      DØ 380 K=1,5
      MUT(J,K)=MUT(J,K)+GAMMA(J)*RL(K)*A5
      DRIVER(J,K)=DRIVER(J,K)+GAMMA(J)*RL(K)*A6
  380 PICKUP(J,K)=PICKUP(J,K)+GAMMA(J)*RL(K)*A7
  385 AIR1=AIR1+2.0*S4*(X*L3-W8)
      AIR2=AIR2+S5*(4.0*(X*L4-W9)-2.0*W7*W9*W9)
  390 CØNTINUE
      B1=B2
      B2=B2+S2
      S1=0.05
      IF(X.LT.9.0) GØ TØ 110
      S1=0.1
      IF(X.LT.29.0) GØ TØ 110
      S1=0.2
      IF(X.LT.39.0) GØ TØ 110
      S1=0.5
      IF(X.LT.79.0) GØ TØ 110
C     THE INTEGRATIØN ENDS HERE
      IF(JKL.NE.0) GØ TØ 780
C     NEXT, THE INDUCTANCES,VØLTAGES,AND PHASE SHIFTS
C     ARE CALCULATED AND PRINTED
  400 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
      CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
      TYPE 410
  410 FØRMAT(1H ,10HDRIVER RES,4X,10HINDUCTANCE,4X,
     18HNØ TURNS,6X,9HSHUNT CAP,5X,9HNØR IM PT)
      Q1=Q0*T1*T1*AIR1/W
      Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
      Q3=Q0*T2*T2*AIR2/W
      Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
      TYPE 420,R6,Q1,N3,C6,Q2
  420 FØRMAT(1H ,1PE12.5,2X,E12.5,2X,0PF8.1,6X,1PE12.5,
     12X,0PF9.6)
      TYPE 430
  430 FØRMAT(1H ,10HPICKUP RES,4X,10HINDUCTANCE,4X,
     18HNØ TURNS,6X,9HSHUNT CAP,5X,9HNØR IM PT)
      TYPE 420,R7,Q3,N4,C7,Q4
      TYPE 440
  440 FØRMAT(1H ,12HDRIVING VØLT,2X,10HSERIES RES,4X,
     18HAMP GAIN,6X,9HINPUT IMP)
      TYPE 450,V0,R0,G5,R9
```

```
 450 FØRMAT(1H ,F5.1,9X,1PE12.5,2X,0PF8.1,6X,1PE12.5)
     TYPE 460,V1
 460 FØRMAT(1H ,22HDISCRIMINATØR VØLTAGE=,1PE12.5)
     TYPE 470
 470 FØRMAT(1H )
     RL(1)=L6
     DØ 480 I=2,5
 480 RL(I)=L2+RL(I-1)
     TYPE 490,RL
 490 FØRMAT(1H ,4(F6.3,8X),F6.3)
     TYPE 470
     DØ 500 I=1,3
     TYPE 510,(TMAG(I,J),J=1,5)
     TYPE 510,(PHASE(I,J),J=1,5)
     TYPE 510,(SHIFT(I,J),J=1,5)
     TYPE 470
 500 CØNTINUE
 510 FØRMAT(1H ,4(1PE12.5,2X),E12.5)
     CALL SENS(SHIFT,RAD,SEN)
C    THE USER NEXT SELECTS ØNE ØF FØUR PØSSIBILITIES
 520 TYPE 530
 530 FØRMAT(' 1 CØIL DESIGN  2 ATTEN.DESIGN  3 DRIFT CHECK
    1  4 CØN CAL')
     TYPE 470
     ACCEPT 540,N5
 540 FØRMAT(I1)
     GØ TØ(550,680,760,1010),N5
C    THE FIRST PØSSIBILITY ALLØWS THE USER TØ ALTER THE
C    CØIL DESIGN BY INPUTTING THE REQUESTED INTEGER DATA
 550 TYPE 560
 560 FØRMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
    1 TURNS')
     TYPE 470
     ACCEPT 570,N1A,N2A,N3A,N4A
 570 FØRMAT(4I)
     IF(N1A*N2A.EQ.0) GØ TØ 580
     GAGE=N1A
     XIN=R1*R5
     XØUT=R2*R5
     XLEN=L3*R5
     TURNS=N2A
     N3=N2A
     N1A=-1
     J1=1
     CALL GAGER(R6)
     GØ TØ 600
 580 IF(N1A.EQ.0) GØ TØ 590
     GAGE=N1A
     XIN=R1*R5
     XØUT=R2*R5
     XLEN=L3*R5
     J1=1
     CALL GAGER(R6)
     N3=TURNS
     GØ TØ 600
 590 IF(N2A.EQ.0) GØ TØ 620
     N3=N2A
```

```
      TURNS=N2A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=0
      CALL GAGER(R6)
  600 TYPE 610,TURNS,GAGE,PERLAY,XLAY,R6
  610 FØRMAT(1H ,6HDRIVER,F6.1,10H TURNS ØF#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  620 IF(N3A*N4A.EQ.0) GØ TØ 630
      GAGE=N3A
      TURNS=N4A
      N4=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      R7=2.0*R7
      GØ TØ 650
  630 IF(N3A.EQ.0) GØ TØ 640
      GAGE=N3A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      R7=2.0*R7
      N4=TURNS
      GØ TØ 650
  640 IF(N4A.EQ.0) GØ TØ 670
      N4=N4A
      TURNS=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=0
      CALL GAGER(R7)
      R7=2.0*R7
  650 TYPE 660,TURNS,GAGE,PERLAY,XLAY,R7
  660 FØRMAT(1H ,6HPICKUP,F6.1,10H TURNS EA#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  670 GØ TØ 400
C     THE SECØND PØSSIBILITY ALLØWS THE USER TØ ALTER THE
C     ATTENUATØR DESIGN BY INPUTTING THE DATA REQUESTED IN
C     E FIELD FØRMAT
  680 TYPE 690
  690 FØRMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
     1 SHUNT CAP')
      TYPE 470
      ACCEPT 700,P1,P2,P3,P4
  700 FØRMAT(4E)
      IF(P1.EQ.0.0) GØ TØ 710
      R0=P1
  710 IF(P2.EQ.0.0) GØ TØ 720
      C6=P2
  720 IF(P3.EQ.0.0) GØ TØ 730
      R9=P3
```

```
 730 IF(P4.EQ.0.0) GØ TØ 740
     C7=P4
 740 Q5=1.0/(W*SQRT(Q1*Q2*C6))
     Q6=SQRT(Q1*Q2/C6)
     Q7=R0/(W*Q1*Q2)
     Q8=1.0/(W*SQRT(Q3*Q4*C7))
     Q9=SQRT(Q3*Q4/C7)
     Q10=R9/(W*Q3*Q4)
     TYPE 750,Q5,Q6,Q7
 750 FØRMAT(1H ,7HDVR CKT,1PE12.5,10H BELØW RES,1PE12.5,
    18H ØPT RES,1PE12.5,11H RES/REACT.)
     TYPE 755,Q8,Q9,Q10
 755 FØRMAT(1H ,7HP-U CKT,1PE12.5,10H BELØW RES,1PE12.5,
    18H ØPT RES,1PE12.5,11H RES/REACT.)
     GØ TØ 400
C    THE THIRD PØSSIBILITY ALLØWS THE USER TØ EXAMINE THE
C    EFFECT ØF DRIFTS ØN THE CIRCUIT
 760 TYPE 770
 770 FØRMAT(1H ,23HSYSTEM DRIFT VARIATIØNS)
     DR1=0.01
     DR2=0.01
     DR3=0.01
     DR4=0.01
     DR5=0.01
     DR6=0.01
     DR7=0.01
     DR8=0.01
     DR9=0.01
     GØ TØ 790
 780 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     GØ TØ (970,1000),JKL
 790 TYPE 800
 800 FØRMAT(1H ,11H% VARIATIØN,3X,13HPARAMETER VAR,1X,
    17HRADIANS,7X,7HDEGREES,7X,10H% ØF RANGE)
     IF(DR1.EQ.0.0) GØ TØ 830
     R6=R6*(1.0+DR1)
     DR100=100.0*DR1
     TYPE 820,DR100
 820 FØRMAT(1H ,F4.1,10X,13HDRIVER RES    $)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     R6=R6/(1.0+DR1)
 830 IF(DR2.EQ.0.0) GØ TØ 850
     R7=R7*(1.0+DR2)
     DR100=100.0*DR2
     TYPE 840,DR100
 840 FØRMAT(1H ,F4.1,10X,13HPICKUP RES    $)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     R7=R7/(1.0+DR2)
 850 IF(DR3.EQ.0.0) GØ TØ 870
     C6=C6*(1.0+DR3)
     DR100=100.0*DR3
     TYPE 860,DR100
 860 FØRMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     C6=C6/(1.0+DR3)
 870 IF(DR4.EQ.0.0) GØ TØ 890
     C7=C7*(1.0+DR4)
     DR100=100.0*DR4
```

```
      TYPE 880,DR100
  880 FØRMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      C7=C7/(1.0+DR4)
  890 IF(DR5.EQ.0.0) GØ TØ 910
      R0=R0*(1.0+DR5)
      DR100=100.0*DR5
      TYPE 900,DR100
  900 FØRMAT(1H ,F4.1,10X,13HSERIES RES    $)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R0=R0/(1.0+DR5)
  910 IF(DR6.EQ.0.0) GØ TØ 930
      R9=R9*(1.0+DR6)
      DR100=100.0*DR6
      TYPE 920,DR100
  920 FØRMAT(1H ,F4.1,10X,13HAMP INPUT RES$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R9=R9/(1.0+DR6)
  930 IF(DR7.EQ.0.0) GØ TØ 950
      V0=V0*(1.0+DR7)
      DR100=100.0*DR7
      TYPE 940,DR100
  940 FØRMAT(1H ,F4.1,10X,13HAPPLIED VØLT.$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      V0=V0/(1.0+DR7)
  950 IF(DR8.EQ.0.0) GØ TØ 980
      F=F*(1.0+DR8)
      DR100=100.0*DR8
      TYPE 960,DR100
  960 FØRMAT(1H ,F4.1,10X,13HFREQUENCY    $)
      JKL=1
      GØ TØ 5
  970 F=F/(1.0+DR8)
      JKL=0
  980 IF(DR9.EQ.0.0) GØ TØ 520
      R5=R5*(1.0+DR9)
      DR100=100.0*DR9
      TYPE 990,DR100
  990 FØRMAT(1H ,F4.1,10X,13HMEAN RADIUS  $)
      JKL=2
      GØ TØ 5
 1000 R5=R5/(1.0+DR9)
      JKL=0
      GØ TØ 520
C     THE FØURTH PØSSIBILITY ENDS CALCULATIØNS
 1010 CALL EXIT
      END
      SUBRØUTINE BESSEL(VAL)
      CØMMØN X,Z,Q1,PI
      IF(Z.GT.5.0) GØ TØ 1510
      L=2.0*Z+3.0
      F1=0.5*Q1*Q1*Q1
      VAL=F1/3.0
      DØ 1500 I=1,L
      AI=I
      F1=-F1*0.25*Z*Z/(AI*AI+AI)
 1500 VAL=VAL+F1/(2.0*AI+3.0)
      GØ TØ 1520
```

```
 1510 X0=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
      X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
      X1=(((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
      X1=(X1-0.187344E-2)/Z+0.7979095
      VAL=(1.0-SQRT(Z)*(X1*CØS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
     1(X*X*X)
 1520 RETURN
      END
      SUBRØUTINE XFØRM(N,TR,R5,U,T)
      CØMMØN /B1/BETA0,BETA1
      CØMPLEX BETA0,BETA1,EX,TR
      DIMENSIØN EX(2),U(10),T(10),TR(2,2)
      EX(1)=CEXP(-BETA0*U(N-1)*T(N-1)/R5)
      EX(2)=1.0/EX(1)
      DØ 1610 I=1,2
      DØ 1610 J=1,2
      K=I+J
      IF(K.EQ.3) GØ TØ 1600
      TR(I,J)=(BETA1+BETA0)*EX(J)
      GØ TØ 1610
 1600 TR(I,J)=(BETA1-BETA0)*EX(J)
 1610 CØNTINUE
      RETURN
      END
      SUBRØUTINE MATRIX(JUMP,V,TR)
      CØMPLEX V,Q,TR
      DIMENSIØN Q(2,2),V(2,2),TR(2,2)
      IF(JUMP.EQ.1) GØ TØ 1720
      DØ 1700 I=1,2
 1700 Q(I,1)=V(I,1)
      DØ 1710 I=1,2
      V(I,1)=(0.0,0.0)
      DØ 1710 J=1,2
 1710 V(I,1)=V(I,1)+TR(I,J)*Q(J,1)
 1720 DØ 1730 I=1,2
 1730 Q(I,2)=V(I,2)
      DØ 1740 I=1,2
      V(I,2)=(0.0,0.0)
      DØ 1740 J=1,2
 1740 V(I,2)=V(I,2)+TR(I,J)*Q(J,2)
      RETURN
      END
      SUBRØUTINE CIRCT(TMAG,PHASE,Q0,T1,T2)
      CØMPLEX MUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
      CØMPLEX DENØM,TNUM,VØLT
      CØMMØN /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
      CØMMØN /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
      CØMMØN /B3/PICKUP,AIR1,AIR2
      DIMENSIØN MUT(3,5),DRIVER(3,5),PICKUP(3,5)
      DIMENSIØN TMAG(3,5),PHASE(3,5)
      REAL L3,L4,N3,N4
      T1=N3/((R2-R1)*L3)
      T2=N4/((R4-R3)*L4)
      Q0=6.300475204E-7*F*R5
      Z1=CMPLX(W*C6*R0,-1.0)
      Z2=CMPLX(W*C7*R9,-1.0)
      Z3=CMPLX(0.0,-R0)
      Z4=CMPLX(0.0,-R9)
```

```
      DØ 1800 I=1,3
      DØ 1800 J=1,5
      Z5=Q0*T1*T2*MUT(I,J)
      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(I,J)+AIR1)
      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
      DENØM=Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*(Z2*(Z7+R7)+Z4)
      TNUM=V0*R9*G5*(0.0,-1.0)*Z5
      VØLT=TNUM/DENØM
      TMAG(I,J)=CABS(VØLT)
 1800 PHASE(I,J)=ATAN2(AIMAG(VØLT),REAL(VØLT))
      RETURN
      END
      SUBRØUTINE PHASET(A,B,C,V1,Ø3)
      DIMENSIØN A(3,5),B(3,5),C(3,5)
      Ø1=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
      Ø2=-(A(2,5)*CØS(B(2,5))-A(2,1)*CØS(B(2,1)))
      Ø3=ATAN2(Ø1,Ø2)
      V1=A(2,1)*SIN(Ø3+B(2,1))
      DØ 1900 I=1,3
      DØ 1900 J=1,5
 1900 C(I,J)=Ø3-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(I,J)
      RETURN
      END
      SUBRØUTINE SENS(Ø,RAD,Ø1)
      DIMENSIØN Ø(3,5)
      Ø9=Ø(1,1)
      Ø0=Ø(1,1)
      DØ 2010 I=2,5
      IF(Ø(1,I).LT.Ø9) GØ TØ 2000
      Ø9=Ø(1,I)
 2000 IF(Ø(1,I).GT.Ø0) GØ TØ 2010
      Ø0=Ø(1,I)
 2010 CØNTINUE
      Ø1=(Ø(1,1)+Ø(1,2)+Ø(1,3)+Ø(1,4)+Ø(1,5))/5.0
      Ø1=Ø1-(Ø(3,1)+Ø(3,2)+Ø(3,3)+Ø(3,4)+Ø(3,5))/5.0
      XLØ=Ø9-Ø0
      PERCT=100.0*XLØ/Ø1
      DEGR1=Ø1*RAD
      DEGR2=XLØ*RAD
      TYPE 2020,Ø1,XLØ,PERCT
 2020 FØRMAT(1H ,12HPHASE SHIFT=,1PE12.5,2X,8HLIFTØFF=,
     1E12.5,2X,2H%=,E12.5)
      TYPE 2030,DEGR1,DEGR2
 2030 FØRMAT(1H ,7HDEGREE:,1PE13.5,5X,E13.5)
      RETURN
      END
      SUBRØUTINE GAGER(RES)
      CØMMØN /B4/G,D1,D2,RLN,T5,N1A,J1,D,E
      PI=3.1415926536
      IF(J1.EQ.1) GØ TØ 2120
      N1A=-1
      D3=0.95*SQRT((D2-D1)*RLN/T5)
      X2=1.0371E-5/(D3*D3)
      Q=40.0
 2100 G=40.0+10.0*(ALØG(X2)-ALØG(.9989+.017*(Q/10.0-1.0)))/2.3
     10259
      IF(ABS(Q-G).LT.1.0E-4) GØ TØ 2110
```

```
      Q=G
      GØ TØ 2100
2110  IG=G
      G=IG
2120  X2=(.9989+.017*(G/10.0-1.0))*10.0**(G/10.0-4.0)
      D3=SQRT(1.0371E-5/X2)
      IF(G.GT.40.0) GØ TØ 2130
      X3=(.460655*ALØG(D3*1.0E3)-.43444)*1.0E-3
      GØ TØ 2140
2130  X3=(98.02228*D3+2.56791E-2)*1.0E-3
2140  ID=(RLN/(D3+X3))
      D=ID
      IE=(D2-D1)/(D3+X3)
      E=IE
      IF(N1A.EQ.-1) GØ TØ 2150
      T5=D*E
2150  RES=T5*X2*(D2+D1)*PI/12.0
      RETURN
      END
      SUBRØUTINE CIRCT1(Ø1,V1,Ø,RAD,SEN)
      DIMENSIØN Ø(3,5),TMAG(3,5),PHASE(3,5)
      CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
      Q1=0.0
      DØ 2200 I=1,3
      DØ 2200 J=1,5
      Q2=Ø1-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
     1+PHASE(I,J)-Ø(I,J)
      IF(ABS(Q1).GT.ABS(Q2)) GØ TØ 2200
      Q1=Q2
2200  CØNTINUE
      Q2NEW=RAD*Q1
      Q3=100.0*Q1/SEN
      TYPE 2210,Q1,Q2NEW,Q3
2210  FØRMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
      RETURN
      END
```

REFLECTION COIL ABOVE MULTIPLE CONDUCTORS, DEFECT

We shall now continue to consider the case of a reflection coil above multiple conductors, as shown in Fig. 4 (p. 7). This program calculates the magnitude and phase of the voltage that is fed to the phase measuring circuits of the phase sensitive eddy-current instruments and is designed to help analyze eddy-current measurements of defects.

The program calculates the magnitude and phase of the induced voltage at five different values of lift-off for two conditions, a nominal condition without defects in any conductor and a varied condition with a defect in a specific conductor, making a total of ten calculations. This allows one to examine the sensitivity to lift-off variations as well as defect variations in a specific conductor. In addition, the program also calculates the phase shift with the discriminator adjusted to give the same phase in the nominal condition with maximum and minimum lift-off. The phase in the nominal condition with minimum lift-off is taken as zero, and all other phase shifts are measured relative to it.

The equations that are evaluated are Eq. (8) for the mutual coupling, Eq. (9) for the driver coil impedance, and Eq. (17) for the pickup coil impedance. The gamma factor for multiple conductors is calculated from Eqs. (24) to (28). Due to the presence of the defect, the self and the mutual impedances are changed and can be calculated from Eq. (21).

The programs are written in both BASIC and FORTRAN for use on the PDP-10. The BASIC program follows.

To use this program, one must first divide all dimensions by the mean radius of the driver coil. Then the following lines must be typed into the program.

```
250     R5 = (numerical value of driver coil mean radius in inches)
260     R1 = (numerical value of normalized driver coil inner radius)
270     R2 = (numerical value of normalized driver coil outer radius)
280     L3 = (numerical value of normalized driver coil length)
290     R3 = (numerical value of normalized pickup coil inner radius)
300     R4 = (numerical value of normalized pickup coil outer radius)
```

310 L4 = (numerical value of normalized pickup coil length)

320 L5 = (numerical value of normalized pickup coil recess from face of driver)

330 L6 = (numerical value of normalized driver coil minimum lift-off)

340 R6 = (numerical value of resistance of driver coil in ohms)

350 R7 = (numerical value of total resistance of both pickup coils in ohms)

360 N3 = (number of turns on driver coil)

370 N4 = (number of turns on each pickup coil)

380 R0 = (output series resistance of driving amplifier in ohms)

390 R9 = (input shunt resistance of pickup amplifier in ohms)

400 C6 = (total shunt capacitance in driving circuit in farads)

410 C7 = (total shunt capacitance in pickup circuit in farads)

420 V0 = (output voltage of driving amplifier in volts)

430 G5 = (gain of pickup amplifier)

440 F = (operating frequency in Hertz)

450 L2 = (numerical value of normalized driver coil lift-off increment)

510 N9 = (total number of conductors + 1)

520 N8 = (number of the specific conductor with a defect, refer to Fig. 4)

760 R8 = (numerical value of normalized defect distance from coil axis)

770 Z7 = (numerical value of defect distance below the surface of the N8-th layer in inches)

780 V5 = (numerical value of normalized defect volume)

790 A0 = (numerical value of shape and orientation factor of defect)

The input data of conductors are typed into the program between the statement numbers 800 and 980, according to the order of appearance from the lowest conductors [refer to Fig. 4 (p. 7)].

```
800      DATA  1E10, K(1), U(1)
810      DATA  T(2), K(2), U(2)
 :        :
 .       DATA  T(N), K(N), U(N)
 :        :
 .       DATA  T(N9-1), K(N9-1), U(N9-1)
(980)    DATA  1(arbitrary number), 1E10, 1
```

where

T(N) = numerical value of thickness of the Nth layer conductor in inches,

K(N) = numerical value of resistivity of the Nth layer conductor in microhm centimeter,

U(N) = numerical value of relative permeability of the Nth layer conductor, and

the (N9-1)th layer denotes the top or surface layer.

The current version of MULTID (BASIC) is limited to a maximum of nine conductors. However, this limitation can be removed easily by adding one DIMENSION statement:

```
60      DIM  T(N9), R(N9), U(N9), S(N9), X(N9), Y(N9) .
```

The program may now be run. The print-out by the computer will have the following format.

```
N              THICK(INCH)     R(MU-OHM CM)  M,SIGMA        U
(1)            (T(1))          (K(1))        .......        (U(1))
(2)            (T(2))          (K(2))        .......        (U(2))
 :               :               :             :              :
(N9-1)         (T(N9-1))       (K(N9-1))     .......        (U(N9-1))
(N9)           (T(N))          (K(N))        .......        (U(N))
R1= (R1)       R2= (R2)        DRIVER LENGTH IS (L3)
R3= (R3)       R4= (R4)        PICK UP LENGTH IS (L4)
COIL MEAN RADIUS (R5) INCHES       OPERATING FREQUENCY (F)
PICK UP RECESSED (L5)
MINIMUM LIFT-OFF (L6)  LIFT-OFF INCREMENT (L2)
DEFECT LOCATED AT R= (R8*R5) INCHES AND
Z= (Z7) INCHES BELOW SURFACE OF (N8)TH LAYER
DRIVER RES     INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT
  (R6)           ......          (N3)          (C6)           .....
```

```
PICKUP RES     INDUCTANCE     NO TURNS     SHUNT CAP     NOR IM PT
  (R7)           ......         (N4)         (C7)          .....
DRIVING VOLT   SERIES RES     AMP GAIN     INPUT IMP
  (V0)           (R0)           (G5)         (R9)
DISCRIMINATOR VOLTAGE IS .....

  (L6)           (L6+L2)        (L6+2L2)     (L6+3L2)      (L6+4L2)

 .....           .....          .....        .....         .....
 .....           .....          .....        .....         .....
  0              .....          .....        .....         .....
LIFT-OFF= ......   RADIANS OR ......   DEGREES
DEFECT VOL IS (V5)   SHAPE & ORIENTATION FACTOR IS (A0)
 ......          ......         ......       ......        ......
1 COIL DESIGN   2 ATTEN. DESIGN   3 DRIFT CHECK   4 CON CAL
 ?
```

The various symbols enclosed in parentheses are used to indicate that the numerical value of the symbol will be printed.

There are five columns of data, one under each value of lift-off. There are three lines in each column. From top to bottom they are: the magnitude of the voltage out of the pickup amplifier, the phase shift between the voltage out of the pickup amplifier and the driving voltage, and the phase shift between the voltage out of the pickup amplifier with the discriminator set to give the same phase shift with minimum lift-off and maximum lift-off. This set of print-outs is for the nominal condition of no defects. The voltage out of the pickup amplifier will be in volts and be either peak-to-peak or RMS, whichever is used for V0, the output voltage of the driving amplifier. For each conductor N, the value of a dimensionless product $R_5{}^2\omega\mu_N\sigma_N$ is also calculated and printed out under the column M,SIGMA. The inductance in henries of the driving coil in air and the normalized imaginary part of the driving coil impedance, with no defect and nominal lift-off (L6+2L2), is also printed. Likewise the inductance in henries of both pickup coils in air and the normalized imaginary part of the pickup coils' impedance with no defect and nominal lift-off is also printed. The maximum phase shift due to lift-off for the nominal condition is given. The location, volume, and shape and orientation factor of the defect are printed. Then, the phase shifts due to the defect are given for five lift-off values. The phase shifts are measured from the nominal condition with no defects and are given in degrees.

The program then enters a branching loop that allows the following options, depending on which of 1, 2, 3, or 4 is typed as input after the question mark.

1. Coil Design

If a 1 is typed by the operator after the question mark, the program will enter the Coil Design Loop. This loop will allow the number of turns on the driver and pickup coils to be varied. The loop will allow the wire gage to be given and then calculate the number of turns and coil resistance, or it will allow the number of turns to be entered and calculate the gage and coil resistance, or both turns and gage can be entered. If zeros are entered for both the gage and turns of either the driver or pickup coils, the present value of these will be retained. The program then starts with the label

DRIVER RES   INDUCTANCE   NO TURNS   SHUNT CAP   NOR IM PT ,

and the remainder of the program is recalculated and printed, with the "new" coil in the circuit. However, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

2. Attenuator Design

This loop will allow the driver series resistance, R0, the driver shunt capacitance, C6, the amplifier input impedance, R9, and the shunt capacitance in the pickup circuit, C7, to be varied. If a 2 is typed after the question mark the computer will respond with

DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP .

The resistance is to be given in ohms, and the capacitance in farads. If zero is typed in for any value, the present value in the computer will be retained. After the input data and a carriage return are typed, the computer will calculate the ratio of resonant frequency to operating frequency for the particular L-C circuit, a very rough value of resistance for minimum temperature drift, and the ratio between the resistance and reactance in the circuit for both the driver and pickup circuits. The program then starts with the label

DRIVER RES   INDUCTANCE   NO TURNS   SHUNT CAP   NOR IM PT ,

and the remainder of the program is recalculated and printed with the "new" attenuator in the circuit. Again, the numerical integrations to calculate M, Z_{DR}, and Z_{PU} do not have to be repeated.

3. Drift Check

This loop calculates the effect of the drift of any of the circuit or sample parameters after the instrument has been calibrated and adjusted. If a 3 is typed as input, the program will respond with the precent variation, the parameter varied, the maximum change in phase (both radians and degrees) of any of the five different phases calculated (five lift-off values with the presence of the defect) and the percent of the range the drift represents. The percent variation of each parameter may be varied independently. The following table gives the parameter, the line number, and the constant to be varied:

Parameter	Line Number	Constant
Driver Resistance	8610	E1
Pickup Resistance	8620	E2
Driver Shunt Cap.	8630	E3
Pickup Shunt Cap.	8640	E4
Series Resistance	8650	E7
Amplifier Input Resistance	8660	E8
Applied Voltage	8670	E9
Frequency	8680	A1
Mean Radius	8690	A2

For example, to put in a 2% variation in the driver coil resistance, one would type:

8610 E1 = .02

The amount that each parameter is varied must be set before the program is run. All of the variations are 0.01 or 1% in the current version of the program. Since the phase shift produced by the parameter variation is quite linear over a range of about 10%, a linear interpolation or extrapolation may be used from the 1% parameter variation. If zero is typed in for any parameter variation, that parameter will not be varied nor will it be typed out in the list of parameter variations. When the calculation is completed and the drifts printed, the program returns to the branch point and repeats the question

1 Coil Design 2 Atten. Design 3 Drift Check 4 Con Cal .

The first seven drifts do not require that the numerical integrations to calculate M, Z_{DR}, and Z_{PU} be repeated, but they must be repeated to calculate the drifts due to frequency and mean radius changes. Therefore, the calculation of these last two drifts requires a considerable amount of computer time.

4. Con Cal

This loop is to continue calculations. If a series of calculations is to be made, a loop may be established at this point. However, in the present version of the program, if a 4 is typed as input, the program will end.

Sample Calculation of MULTID

Let us suppose we wish to design a reflection-type coil to measure a defect in a sodium layer that has a thickness of 10 mils and a resistivity of 4.99 μΩ-cm. Above the sodium layer, there is a conductor 15 mils thick with a resistivity of 75 μΩ-cm. Below the sodium layer, there is a very thick material with a resistivity of 130 μΩ-cm. The driver coil has a mean radius of 0.06 in., inner and outer radii of 0.045 and 0.075 in., and a length of 0.018 in. The pickup coils have inner and outer radii of 0.021 and 0.042 in., a length of 0.006 in., and are mounted flush with the ends of the driver coil. The driver coil has 252 turns of No. 48 wire with a resistance of 59.06 Ω, and the pickup coils have 450 turns each of No. 58 wire with a resistance of 1067.4 Ω for both coils. The driver series and the pickup amplifier input resistances are both chosen to be 1 MΩ. The shunt capacitances in both circuits are chosen to be 1 pF. This corresponds to practically infinite source and detector impedances, so that only the mutual coupling, M, affects the phases. The minimum lift-off is taken to be 0.003 in. with lift-off increments of 0.00075 in. The defect is located 5 mils below the surface of the sodium layer and 60 mils from the axis of the coil. The defect is a spherical defect with a radius of 2.5 mils.

Thus, the shape and orientation factor is equal to one. Other shape and orientation factors are given elsewhere.[11]

The frequency is 100 KHz, the output voltage of the driving amplifier is 10 V, and the gain of the pickup amplifier is unity (a unity gain allows the actual gain needed in the amplifier to be calculated by dividing the maximum output voltage with unity gain into 10).

The program MULTID is assumed to be in the active core, and the following information is typed into the computer. All linear dimensions are normalized by dividing by the coil mean radius, except for the coil mean radius, which is in inches.

```
250     R5 = .06
260     R1 = .75
270     R2 = 1.25
280     L3 = .3
290     R3 = .35
300     R4 = .7
310     L4 = .1
320     L5 = 0
330     L6 = .05
340     R6 = 59.06
350     R7 = 1067.4
360     N3 = 252
370     N4 = 450
380     R0 = 1E6
390     R9 = 1E6
400     C6 = 1E-12
410     C7 = 1E-12
420     V0 = 10
430     G5 = 1
440     F = 100E3
450     L2 = .0125
```

[11] C. V. Dodd, W. E. Deeds, J. W. Luquire, and W. G. Spoeri, *Some Eddy-Current Problems and Their Integral Solutions*, ORNL-4384 (April 1969).

```
760     R8 = 1
770     Z7 = .005
780     V5 = 3.030811E-4
790     A0 = 1
800     DATA  1E10, 130, 1
810     DATA  .01, 4.99, 1
820     DATA  .015, 75, 1
830     DATA  1, 1E10, 1
```

The program may now be run with the following results. The data inputed from the terminal by the user are underlined. A carriage return must be typed by the user at the end of each input line.

```
MULTID(BASIC)

N              THICK(INCH)    R(MU-0HM CM)   M,SIGMA        U
 1              1.00000E+10    130            1.41065        1
 2              0.01           4.99           36.7503        1
 3              0.015          75             2.44512        1
 4              1              1.00000E+10    0              1
R1= 0.75       R2= 1.25       DRIVER LENGTH IS 0.3
R3= 0.35       R4= 0.7        PICK UP LENGTH IS 0.1
C0IL MEAN RADIUS 0.06 INCHES     0PERATING FREQUENCY 100000
PICK UP RECESSED 0
MIN LIFT-0FF= 0.05 LIFT-0FF INCREMENT= 0.0125
DEFECT L0CATED AT R= 0.06 INCHES AND
Z= 0.005 INCHES BEL0W SURFACE 0F 2 TH LAYER
DRIVER RES     INDUCTANCE     N0 TURNS       SHUNT CAP      N0R IM PT
 59.06          2.22053E-4     252            1.00000E-12    0.827304
PICKUP RES     INDUCTANCE     N0 TURNS       SHUNT CAP      N0R IM PT
 1067.4         3.20001E-4     450            1.00000E-12    0.991584
DRIVING V0LT   SERIES RES     AMP GAIN       INPUT IMP
 10             1000000        1              1000000
DISCRIMINAT0R V0LTAGE IS-1.86118E-6

 0.05           0.0625         0.075          0.0875         0.1

 5.66040E-5     5.41995E-5     5.19010E-5     4.97043E-5     4.76056E-5
-0.994593      -0.995917      -0.997404      -0.999041      -1.00081
 0              1.36040E-4     1.70328E-4     1.19887E-4     1.49012E-8
LIFT-0FF = 1.70328E-4 RADIANS 0R 9.75907E-3 DEGREES
DEFECT V0L IS 3.03081E-4 SHAPE & 0RIENTATI0N FACT0R IS 1
-9.42610E-3    -9.44360E-3    -9.45769E-3    -9.46964E-3    -9.47690E-3
1 C0IL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 C0N CAL
 ?1

DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS
 ?48,0,58,0
DRIVER 252 TURNS 0F # 48 WIRE 12 /LAYER 21 LAYERS 53.1236 0HM
PICKUP 598 TURNS EA # 58 WIRE 13 /LAYER 46 LAYERS 1344.82 0HMS T0TAL
DRIVER RES     INDUCTANCE     N0 TURNS       SHUNT CAP      N0R IM PT
 53.1236        2.22053E-4     252            1.00000E-12    0.827304
PICKUP RES     INDUCTANCE     N0 TURNS       SHUNT CAP      N0R IM PT
 1344.82        5.65105E-4     598            1.00000E-12    0.991584
DRIVING V0LT   SERIES RES     AMP GAIN       INPUT IMP
 10             1000000        1              1000000
DISCRIMINAT0R V0LTAGE IS-2.47288E-6

 0.05           0.0625         0.075          0.0875         0.1

 7.52070E-5     7.20124E-5     6.89584E-5     6.60399E-5     6.32514E-5
-0.994917      -0.996241      -0.997728      -0.999364      -1.00114
 0              1.36048E-4     1.70335E-4     1.19887E-4     1.49012E-8
LIFT-0FF = 1.70335E-4 RADIANS 0R 9.75949E-3 DEGREES
DEFECT V0L IS 3.03081E-4 SHAPE & 0RIENTATI0N FACT0R IS 1
-9.42524E-3    -9.44360E-3    -9.45854E-3    -9.46836E-3    -9.47604E-3
1 C0IL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 C0N CAL
 ?2
```

```
DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP
 ?8.0E2,1.3E-10,3.3E3,7.9E-11
DVR CT 10.2988 BELØW RES 1188.75 ØPT RES 6.93088 RES/REACTANCE
P-U CT 7.56445 BELØW RES 2663.27 ØPT RES 9.37293 RES/REACTANCE
DRIVER RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 53.1236       2.22053E-4     252            1.30000E-10    0.827304
PICKUP RES     INDUCTANCE     NØ TURNS       SHUNT CAP      NØR IM PT
 1344.82       5.65105E-4     598            7.90000E-11    0.991584
DRIVING VØLT   SERIES RES     AMP GAIN       INPUT IMP
 10            800            1              3300
DISCRIMINATØR VØLTAGE IS-3.37434E-3

 0.05          0.0625         0.075          0.0875         0.1

 6.19677E-2    5.93711E-2     5.68856E-2     5.45074E-2     5.22324E-2
-1.25436      -1.25674       -1.25923       -1.26183       -1.26453
 0             1.41263E-5     8.21054E-6    -1.43051E-6     0
LIFT-ØFF = 1.41263E-5 RADIANS ØR 8.09378E-4 DEGREES
DEFECT VØL IS 3.03081E-4 SHAPE & ØRIENTATIØN FACTØR IS 1
-9.25662E-3   -9.28992E-3    -9.31980E-3    -9.34541E-3    -9.36676E-3
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?3

SYSTEM DRIFT VARIATIØNS
% VARIATN     PARAMETER      RADIAN         DEGREE         % ØF RANGE
 1            DRIVER RES     -8.42959E-5    -4.82980E-3     51.8458
 1            PICKUP RES     -1.13413E-4    -6.49808E-3     69.754
 1            DVR SHUNT CAP  -2.28956E-4    -1.31182E-2     140.819
 1            P-U SHUNT CAP  -6.56769E-4    -3.76301E-2     403.943
 1            SERIES RES      1.64838E-3     9.44454E-2    -1013.83
 1            AMP INPUT RES   6.78599E-5     3.88809E-3    -41.7369
 1            APPLIED VØLT   -8.04409E-4    -4.60893E-2     494.749
 1            FREQUENCY      -6.60783E-3    -0.378601       4064.12
 1            MEAN RADIUS    -8.00069E-3    -0.458406       4920.79
1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL
 ?4
```

The user has exercised all the design options available, and these options may be repeated, omitted, or taken in any order. The BASIC version of the program MULTID follows.

```
1   REM MULTID(BASIC)
10 REM REFLECTIØN CØIL FØR DEFECT ØF MULTILAYER CØNDUCTØRS
40 DIM A(5),B(5),C(5),D(5),E(5),F(5)
50 DIM M(5),P(5),Q(5)
199 REM CØNSTANT
200 P9=3.14159
210 P8=180/P9
249 REM CØIL DATA
250R5=.06
260R1=.75
270R2=1.25
280L3=.3
290R3=.35
300R4=.7
310L4=.1
320L5=0
330L6=.05
340R6=59.06
350R7=1067.4
360N3=252
370N4=450
379 REM CIRCUIT DATA
380R0=1E6
390R9=1E6
400C6=1E-12
410C7=1E-12
420V0=10.0
430G5=1
440F=100E3
450L2=.0125
470L7=L3-2*(L4+L5)
480L8=L7+L4
490L9=L5+2*L6
499 REM CØNDUCTØR DATA
500 DIM L(5),G(5),H(5),I(5),J(5)
510 N9=4
520 N8=2
529 REM READ T,K,U
530 PRINT "N","THICK(INCH)","R(MU-ØHM CM)","M,SIGMA","U"
535 FØR N=1 TØ N9
537 READ T(N),R(N),U(N)
539 NEXT N
540 GØ SUB 600
550 FØR N=1 TØ N9
560 PRINT N,T(N),R(N),S(N),U(N)
570 NEXT N
580 GØ TØ 750
599 REM SUBRØUTINE FØR M
600 W=2*P9*F
610 FØR N=1 TØ N9
630 S(N)=0
640 IF R(N)>1E9 THEN 660
650 S(N)=.5094*U(N)*F*R5*R5/R(N)
660 NEXT N
670 D0=6.0805E-2*F*R5*R5/R(N8)
680 RETURN
750 T(N9)=0
759 REM DATA ØF DEFECT PØSITIØN, VØLUME, AND SHAPE & ØRIENTATIØN
```

```
760 R8=1
770 Z7=.005
780 V5=3.030811E-4
790 A0=1
799 REM DATA
800 DATA 1E10,130,1
810 DATA .01,4.99,1
820 DATA .015,75,1
830 DATA 1,1E10,1
999 REM PRINT CØIL DATA
1000 PRINT "R1=";R1,"R2=";R2,"DRIVER LENGTH IS";L3
1010 PRINT"R3=";R3,"R4=";R4,"PICK UP LENGTH IS";L4
1020 PRINT "CØIL MEAN RADIUS";R5;"INCHES      ØPERATING FREQUENCY";F
1030 PRINT "PICK UP RECESSED";L5
1040 PRINT "MIN LIFT-ØFF=";L6;"LIFT-ØFF INCREMENT=";L2
1050 PRINT "DEFECT LØCATED AT R=";R8*R5;"INCHES AND"
1060 PRINT "Z=";Z7;"INCHES BELØW SURFACE ØF";N8;"TH LAYER"
1100 REM PRØGRAM BEGINS
1110 REM FØR INTEGRATIØNS
1120 GØ SUB 1500
1129 REM WITH NØ DEFECT
1130 REM FØR INDUCTANCES AND CIRCUIT; MAGNITUDE AND PHASE
1135 Q=0
1140 GØ SUB 6000
1150 REM FØR DISCRIMINATØR VØLTAGE AND PHASE SHIFT
1160 GØ SUB 6500
1170 REM FØR PRINTING ØF RESULTS
1180 GØ SUB 6700
1190 REM FØR LIFT-ØFF ERRØR
1200 GØ SUB 7000
1210 REM WITH DEFECT
1220 Q=V5*A0*D0
1230 REM FØR MAGNITUDE AND PHASE
1240 GØ SUB 6000
1250 REM FØR PHASE SHIFT
1260 GØ SUB 7070
1400 REM FØR CØIL AND ATTENUATØR DESIGNS, AND DRIFT
1410 GØ TØ 7200
1499 REM SUBRØUTINE FØR INTEGRATIØN
1500 A3=0
1510 A4=0
1519 REM IN SUBRØUTINE FØR INTEGRATIØN
1520 FØR J=1 TØ 5
1530 A(J)=0
1540 B(J)=0
1550 C(J)=0
1560 D(J)=0
1570 E(J)=0
1580 F(J)=0
1590 G(J)=0
1600 H(J)=0
1610 I(J)=0
1612 J(J)=0
1614 NEXT J
1620 LET S2=5
1630 B1=0
1640 B2=5
1650 S1=1E-2
```

```
1660 FØR X=B1+S1/2 TØ B2 STEP S1
1670 GØ SUB 2000
1680 NEXT X
1690 B1=B2
1700 B2=B2+S2
1710 S1=.05
1720 IF X<9 THEN 1660
1730 S1=.1
1740 IF X<29 THEN 1660
1750 S1=.2
1760 IF X<39 THEN 1660
1770 S1=.5
1780 IF X<79 THEN 1660
1790 RETURN
1998 REM SUBRØUTINE FØR L-FACTØR AND INTEGRANTS
1999 REM FØR J-FACTØR
2000 GØ SUB 2700
2010 W5=0
2020 W2=0
2030 W6=0
2040 W7=0
2050 W4=1
2060 W8=1
2070 W3=1
2080 IF X*L5>20 THEN 2100
2090 W5=EXP(-X*L5)
2100 IF X*L2>20 THEN 2120
2110 W2=EXP(-X*L2)
2120 IF X*L6>20 THEN 2140
2130 W6=EXP(-X*L6)
2140 IF X*L7>20 THEN 2160
2150 W7=EXP(-X*L7)
2160 IF X*L4>15 THEN 2220
2170 W4=1-EXP(-X*L4)
2180 IF X*L8>15 THEN 2220
2190 W8=1-EXP(-X*L8)
2200 IF X*L3>15 THEN 2220
2210 W3=1-EXP(-X*L3)
2220 IF X>30 THEN 2460
2230 IF X*L9>20 THEN 2460
2240 A5=W6*W6*W3*W4*W5*W8*S3
2250 A6=W6*W6*W3*W3*S4
2260 A7=W6*W6*W4*W4*W5*W5*W8*W8*S5
2261 REM IN SUBRØUTINE FØR L-FACTØR AND INTEGRANT
2262 A8=W6*W3*S6
2264 A9=W6*W4*W5*W8*S7
2270 L(1)=1
2280 FØR J=2 TØ 5
2290 L(J)=0
2300 IF J*X*L2>20 THEN 2320
2310 L(J)=W2*L(J-1)
2320 NEXT J
2329 REM FØR GAMMA FACTØR
2330 GØ SUB 3200
2340 FØR J=1 TØ 5
2342 Q1=K1*L(J)*L(J)
2344 Q2=-N5*L(J)*L(J)
```

```
2346 Q3=K2*L(J)
2348 Q4=N6*L(J)
2350 A(J)=A(J)+Q2*A5
2360 B(J)=B(J)+Q1*A5
2370 C(J)=C(J)+Q2*A6
2380 D(J)=D(J)+Q1*A6
2390 E(J)=E(J)+Q2*A7
2400 F(J)=F(J)+Q1*A7
2410 G(J)=G(J)+Q3*A8
2420 H(J)=H(J)+Q4*A8
2430 I(J)=I(J)+Q3*A9
2440 J(J)=J(J)+Q4*A9
2450 NEXT J
2460 A3=A3+2*(X*L3-W3)*S4
2470 A4=A4+(4*(X*L4-W4)-2*W7*W4*W4)*S5
2480 RETURN
2699 REM SUBRØUTINE FØR J5=J(R1,R2)/X↑3,J6=J(R3,R4)/X↑3
2700 R=R1
2710 GØ SUB 2900
2720 J1=Q2
2730 R=R2
2740 GØ SUB 2900
2750 J5=Q2-J1
2760 R=R3
2770 GØ SUB 2900
2780 J3=Q2
2790 R=R4
2800 GØ SUB 2900
2810 J6=Q2-J3
2820 S3=S1*J5*J6
2830 S4=S1*J5*J5
2840 S5=S1*J6*J6
2849 REM IN SUBRØUTINE FØR J5, J6, AND J1
2850 GØ SUB 3060
2860 S6=S1*J5*J1
2870 S7=S1*J6*J1
2880 RETURN
2899 REM SUBRØUTINE FØR Q2=J(R,0)*X↑3
2900 Z=X*R
2910 IF Z>5 THEN 3000
2920 Q1=R*R*R/2
2930 Q2=Q1/3
2940 Q3=INT(2*Z)+3
2950 FØR Q=1 TØ Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 GØ TØ 3050
3000 Q1=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
3010 Q1=((Q1-0.1730503)/Z+0.7034845)/Z-0.064109E-3
3020 Q2=(((-5.817517/Z+2.105874)/Z-0.6896196)/Z+0.4952024)/Z
3030 Q2=(Q2-0.187344E-2)/Z+0.7979095
3040 Q2=(1-SQR(Z)*(Q2*CØS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3059 REM SUBRØUTINE FØR J1(X*R)
3060 Z=X*R8
3070 IF Z>3 THEN 3130
3080 Q1=Z*Z
```

```
3090 Q2=((2.1E-11*Q1-5.38E-9)*Q1+6.757E-7)*Q1-5.42443E-5
3100 Q2=((Q2*Q1+2.60415E-3)*Q1-6.25E-2)*Q1+.5
3110 J1=Z*Q2
3120 GØ TØ 3180
3130 Q1=(((-.14604057/Z+.27617679)/Z-.20210391)/Z+4.61835E-3)/Z
3140 Q1=((Q1+.14937)/Z+4.68E-6)/Z+.79788456
3150 Q2=(((-.21262014/Z+.19397232)/Z+6.022188E-2)/Z-1.7222733E-1)/Z
3160 Q2=((Q2+5.085E-4)/Z+.37498836)/Z-2.35619449+Z
3170 J1=Q1*CØS(Q2)/SQR(Z)
3180 RETURN
3194 REM SUBRØUTINE FØR GAMMA FACTØR (K1,N5) AND
3196 REM FØR DEFECT PART (K2,N6)=SUM(L=1,2) ØF
3198 REM V(M,N7)L,2*EXP((-1)(L)*U(M)*BETA(M)*Z)/V(K,N7)2,2
3199 REM FØR BETA(X1,Y1)N
3200 Q1=X*X
3210 Q2=Q1*Q1
3220 Q=0
3230 N=N9
3240 M1=S(N)
3250 U1=U(N)
3260 GØ SUB 5000
3270 X(N)=X1
3280 Y(N)=Y1
3290 Q=Q+X1*T(N)/R5
3300 IF Q>20 THEN 3340
3310 IF N=1 THEN 3340
3320 N=N-1
3330 GØ TØ 3240
3340 N7=N
3350 REM FØR GAMMA FACTØR
3360 V3=X(N+1)-X(N)
3370 V4=Y(N+1)-Y(N)
3380 V7=X(N+1)+X(N)
3390 V8=Y(N+1)+Y(N)
3400 X0=X(N+1)
3410 Y0=Y(N+1)
3420 IF N8<N7+2 THEN 3510
3430 FØR N=N7+2 TØ N8
3440 X1=X(N)
3450 Y1=Y(N)
3460 GØ SUB 5300
3470 GØ SUB 5580
3480 X0=X1
3490 Y0=Y1
3500 NEXT N
3510 IF N8<N7+1 THEN 3600
3520 N=N8
3530 T9=T(N)-Z7
3540 GØ SUB 5710
3550 V1=(V3*Q1+V4*Q2)/Q6+(V7*Q1-V8*Q2)*Q6
3560 V2=(V4*Q1-V3*Q2)/Q6+(V8*Q1+V7*Q2)*Q6
3570 IF N8<N7+2 THEN 3590
3580 N7=N8-1
3590 GØ TØ 3680
3600 IF N8<N7 THEN 3660
3610 T9=Z7
3620 GØ SUB 5710
3630 V1=2*(X(N+1)*Q1+Y(N+1)*Q2)/Q6
```

```
3640 V2=2*(Y(N+1)*Q1-X(N+1)*Q2)/Q6
3650 GØ TØ 3680
3660 V1=V2=0
3670 REM V(N8+1,N9)
3680 FØR N=N7+2 TØ N9
3690 X1=X(N)
3700 Y1=Y(N)
3710 GØ SUB 5300
3720 GØ SUB 5500
3730 X0=X1
3740 Y0=Y1
3750 NEXT N
3760 V9=V7/V8+V8/V7
3770 K1=(V3/V8+V4/V7)/V9
3780 N5=(V4/V8-V3/V7)/V9
3790 K2=(V1/V8+V2/V7)/V9
3800 N6=(V2/V8-V1/V7)/V9
3810 RETURN
4999 REM SUBRØUTINE FØR BETA(X1,Y1)
5000 IF M1<Q1*1E-5 THEN 5050
5010 Q3=SQR(Q2+M1*M1)
5020 X1=.707106781*SQR(Q3+Q1)/U1
5030 Y1=.707106781*SQR(Q3-Q1)/U1
5040 GØ TØ 5070
5050 X1=X/U1
5060 Y1=0
5070 RETURN
5299 REM SUBRØUTINE FØR XFØRMATIØM MATRIX T
5300 Q2=X1+X0
5310 Q1=X1-X0
5320 Q4=Y1+Y0
5330 Q3=Y1-Y0
5340 Q5=U(N-1)*T(N-1)/R5
5350 Q6=EXP(Q5*X0)
5360 Q7=CØS(Q5*Y0)
5370 Q8=SIN(Q5*Y0)
5380 T1=(Q2*Q7+Q4*Q8)/Q6
5390 T2=(Q4*Q7-Q2*Q8)/Q6
5400 T3=(Q1*Q7-Q3*Q8)*Q6
5410 T4=(Q3*Q7+Q1*Q8)*Q6
5420 T5=(Q1*Q7+Q3*Q8)/Q6
5430 T6=(Q3*Q7-Q1*Q8)/Q6
5440 T7=(Q2*Q7-Q4*Q8)*Q6
5450 T8=(Q4*Q7+Q2*Q8)*Q6
5460 RETURN
5499 REM SUBRØUTINE FØR XFØRMATIØN MATRIX V
5500 Q1=V1
5510 Q2=V2
5520 V1=(Q1*X1-Q2*Y1)*2
5530 V2=(Q1*Y1+Q2*X1)*2
558003=V3
559004=V4
560007=V7
561008=V8
5620 V3=T1*Q3-T2*Q4+T3*Q7-T4*Q8
5630 V4=T2*Q3+T1*Q4+T4*Q7+T3*Q8
5640 V7=T5*Q3-T6*Q4+T7*Q7-T8*Q8
5650 V8=T6*Q3+T5*Q4+T8*Q7+T7*Q8
```

```
5660 RETURN
5700 REM USEFUL SUBRØUTINE
5710 CO=U(N)*T9/R5
5720 Q6=EXP(CO*X(N))
5730 Q1=CØS(CO*Y(N))
5740 Q2=SIN(CO*Y(N))
5750 RETURN
5999 REM SUBRØUTINE FØR CIRCUIT, MAGNITUDE, AND PHASE
6000N1=N3/((R2-R1)*L3)
6010N2=N4/((R4-R3)*L4)
6020Q0=6.300475204E-7*F*R5
6030 W1=W*C6*R0
6040 W2=W*C7*R9
6050 W3=1-W1*W2
6060 W4=W1+W2
6069 REM IN SUBRØUTINE FØR CIRCUIT, MAGNITUDE, AND PHASE
6080 FØR J=1 TØ 5
6090 Z8=Q0*N1*N2*(A(J)+Q*(G(J)*I(J)-H(J)*J(J)))
6100 Z9=Q0*N1*N2*(B(J)+Q*(G(J)*J(J)+H(J)*I(J)))
6110 Z=Q0*N1*N1*(C(J)+Q*(G(J)*G(J)-H(J)*H(J)))
6120 Z2=Q0*N1*N1*(D(J)+A3+Q*2*G(J)*H(J))
6130 Z1=Q0*N2*N2*(E(J)+Q*(I(J)*I(J)-J(J)*J(J)))
6140 Z3=Q0*N2*N2*(F(J)+A4+Q*2*I(J)*J(J))
6150 Q1=R0+R6+Z-W1*Z2
6160 Q2=R9+R7+Z1-W2*Z3
6170 Q3=Z2+W1*(R6+Z)
6180 Q4=Z3+W2*(R7+Z1)
6190 Q5=Z8*Z8-Z9*Z9
6200 Q6=2*Z8*Z9
6210 Q7=Q1*Q2-Q3*Q4-(W3*Q5-W4*Q6)
6220 Q8=Q1*Q4+Q3*Q2-(W4*Q5+W3*Q6)
6230 Q9=Z8*Q7+Z9*Q8
6240 W5=Z9*Q7-Z8*Q8
6250 M(J)=G5*R9*V0*SQR(Q9*Q9+W5*W5)/(Q7*Q7+Q8*Q8)
6260 P(J)=ATN(W5/Q9)
6270 IF Q9>0 THEN 6290
6280 P(J)=P(J)+SGN(W5)*P9
6290 NEXT J
6310 RETURN
6499 REM IN SUBRØUTINE FØR DISCRIMINATØR VØLTAGE AND PHASE SHIFT
6500 Q1=M(5)*SIN(P(5))-M(1)*SIN(P(1))
6510 Q2=-M(5)*CØS(P(5))+M(1)*CØS(P(1))
6520 Q3=ATN(Q1/Q2)
6530 IF Q2>0 THEN 6550
6540 Q3=Q3+SGN(Q1)*P9
6550 V1=M(1)*SIN(Q3+P(1))
6555 Ø1=Q3
6556 Ø2=V1
6570 FØR J=1 TØ 5
6580 Q(J)=Q3-ATN(V1/SQR(M(J)*M(J)-V1*V1))+P(J)
6590 NEXT J
6610 RETURN
6699 REM SUBRØUTINE FØR PRINTING RESULTS
6700PRINT"DRIVER RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6710PRINTR6,Q0*N1*N1*A3/W,N3,C6,(D(3)+A3)/A3
6720PRINT"PICKUP RES","INDUCTANCE","NØ TURNS","SHUNT CAP","NØR IM PT"
6730PRINTR7,Q0*N2*N2*A4/W,N4,C7,(F(3)+A4)/A4
```

```
6740PRINT "DRIVING VØLT","SERIES RES","AMP GAIN","INPUT IMP"
6750PRINTVO,RO,G5,R9
6760PRINT "DISCRIMINATØR VØLTAGE IS";V1
6770 PRINT
6780 PRINT L6,L6+L2,L6+2*L2,L6+3*L2,L6+4*L2
6789 REM IN SUBRØUTINE FØR PRINTING RESULTS
6800 PRINT
6810 PRINT M(1),M(2),M(3),M(4),M(5)
6820 PRINT P(1),P(2),P(3),P(4),P(5)
6830 PRINT Q(1),Q(2),Q(3),Q(4),Q(5)
6850 RETURN
6999 REM SUBRØUTINE FØR LIFT-ØFF
7000 Q1=Q(1)
7010 FØR J=2 TØ 5
7020 IF ABS(Q1)>ABS(Q(J)) THEN 7040
7030 Q1=Q(J)
7040 NEXT J
7050 PRINT "LIFT-ØFF =";Q1;"RADIANS ØR";Q1*P8;"DEGREES"
7060 RETURN
7069 REM SUBRØUTINE FØR PHASE SHIFT
7070 PRINT"DEFECT VØL IS";V5;"SHAPE & ØRIENTATIØN FACTØR IS";AO
7080 Q2=0
7090 FØR J=1 TØ 5
7100 Q1=Ø1-ATN(V1/SQR(M(J)*M(J)-V1*V1))+P(J)-Q(J)
7110 Q2=Q2+Q1
7120 PRINT Q1*P8,
7130 NEXT J
7140 Ø=Q2/5
7150 RETURN
7199 REM FØR CØIL DESIGN, ATTENUATØR, DRIFT, AND EXIT
7200PRINT"1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK  4 CØN CAL"
7210INPUT N5
7220PRINT
7230ØN N5 GØ TØ 7300,8200,8600,9900
7299 REM FØR CØIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FØR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 GØ SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER";N3;"TURNS ØF #";G;"WIRE";
7390 PRINT Q7;"/LAYER";Q8;"LAYERS";R6;"ØHM"
7399 REM FØR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
7430 W2=R4
7440 W3=L4
7450 GØ SUB 7510
7460 N4=Q2
7470 R7=2*Q9
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIRE";
7490 PRINT Q7;"/LAYER";Q8;"LAYERS";R7;"ØHMS TØTAL"
7500 GØ TØ 1135
```

```
7509 REM SUBRØUTINE FØR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FØR GAGE
7540 G=Q1
7550 IF G>.5 THEN 7640
7560 Q5=.95*SQR((W2-W1)*W3/Q2)
7570 Q6=1.0371E-5/Q5/Q5
7580 G0=40
7590 G=40+10*(LØG(Q6)-LØG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 GØ TØ 7590
7630 G=INT(G)
7639 REM FØR TURN NUMBER AND R6
7640 Q6=(.9989+.017*(G/10-1))*10↑(G/10-4)
7650 Q5=SQR(1.0371E-5/Q6)
7660 IF G> 40 THEN 7690
7670 Q5=(.460655*LØG(Q5*1E3)-.43444)*1E-3+Q5
7680 GØ TØ 7700
7690 Q5=(98.02228*Q5+2.56791E-2)*1E-3+Q5
7700 Q7=INT(W3/Q5)
7710 Q8=INT((W2-W1)/Q5)
7720 IF Q2>.5 THEN 7740
7730 Q2=Q7*Q8
7740 Q9=Q2*Q6*(W2+W1)*P9/12
7750 RETURN
8199 REM FØR ATTENUATØR DESIGN
8200 PRINT "DRIVER SERIES RES, SHUNT CAP, PICK-UP SHUNT RES, SHUNT CAP"
8210 INPUT Q1,Q2,Q3,Q4
8220 IF Q1=0 THEN 8240
8230 R0=Q1
8240 IF Q2=0 THEN 8260
8250 C6=Q2
8260 IF Q3=0 THEN 8280
8270 R9=Q3
8280 IF Q4=0 THEN 8300
8290 C7=Q4
8300 Q1=Q0*N1*N1*(D(3)+A3)/W
8310 Q2=Q0*N2*N2*(F(3)+A4)/W
8320 PRINT "DVR CT";1/(W*SQR(Q1*C6));"BELØW RES";
8330 PRINT SQR(Q1/C6);"ØPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELØW RES";
8350 PRINT SQR(Q2/C7);"ØPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 GØ TØ 1135
8599 REM FØR DRIFTS
8600 PRINT"SYSTEM DRIFT VARIATIØNS"
8610 E1=.01
8620 E2=.01
8630 E3=.01
8640 E4=.01
8650 E7=.01
8660 E8=.01
8670 E9=.01
8680 A1=.01
8690 A2=.01
8710 PRINT "% VARIATN","PARAMETER","RADIAN","DEGREE","% ØF RANGE"
8720 IF E1=0 THEN 8770
```

```
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 GØ SUB 9320
8760 R6=R6/(1+E1)
8770 IF E2=0 THEN 8820
8780 R7=R7*(1+E2)
8790 PRINT 100*E2,"PICKUP RES",
8800 GØ SUB 9320
8810 R7=R7/(1+E2)
8820 IF E3=0 THEN 8870
8830 C6=C6*(1+E3)
8840 PRINT 100*E3,"DVR SHUNT CAP",
8850 GØ SUB 9320
8860 C6=C6/(1+E3)
8870 IF E4=0 THEN 8920
8880 C7=C7*(1+E4)
8890 PRINT 100*E4,"P-U SHUNT CAP",
8900 GØ SUB 9320
8910 C7=C7/(1+E4)
8920 IF E7=0 THEN 8970
8930 R0=R0*(1+E7)
8940 PRINT 100*E7,"SERIES RES",
8950 GØ SUB 9320
8960 R0=R0/(1+E7)
8970 IF E8=0 THEN 9020
8980 R9=R9*(1+E8)
8990 PRINT 100*E8,"AMP INPUT RES",
9000 GØ SUB 9320
9010 R9=R9/(1+E8)
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VØLT",
9050 GØ SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 GØ SUB 9300
9110 F=F/(1+A1)
9120 IF A2=0 THEN 9170
9130 R5=R5*(1+A2)
9140 PRINT 100*A2,"MEAN RADIUS",
9150 GØ SUB 9300
9160 R5=R5/(1+A2)
9170 GØ TØ 7200
9299 REM SUBRØUTINE FØR DRIFT
9300 GØ SUB 600
9310 GØ SUB 1500
9315 Q=V5*A0*D0
9320 GØ SUB 6000
9330 Q1=0
9350 FØR J=1 TØ 5
9360 Q2=Ø1-ATN(Ø2/SQR(M(J)*M(J)-Ø2*Ø2))+P(J)-Q(J)
9370 IF ABS(Q1)>ABS(Q2) THEN 9390
9380 Q1=Q2
9390 NEXT J
9410 PRINT Q1,180*Q1/P9,100*Q1/Ø
9420 RETURN
9900 END
```

MULTID, FORTRAN Version

The FORTRAN version of MULTID is very similar to the BASIC version. The line numbers given are only for identification and editing purposes and have no effect on the actual execution of the FORTRAN program. The data must be typed in the seventh column, or six spaces must first be typed. The data are input as follows:

00250	R5 = (coil mean radius in inches)
00260	R1 = (normalized inner radius of driver coil)
00270	R2 = (normalized outer radius of driver coil)
00280	L3 = (normalized length of driver coil)
00290	R3 = (normalized inner radius of pickup coil)
00300	R4 = (normalized outer radius of pickup coil)
00310	L4 = (normalized length of pickup coil)
00320	L5 = (normalized length of recess of each pickup coil from the face of the driver coil)
00330	L6 = (normalized minimum lift-off of the driver coil)
00340	R6 = (resistance of driver coil in ohms)
00350	R7 = (resistance of both pickup coils in ohms)
00360	N3 = (number of turns on the driver coil)
00370	N4 = (number of turns on each pickup coil)
00380	R0 = (driver amplifier series resistance in ohms)
00390	R9 = (pickup amplifier shunt resistance in ohms)
00400	C6 = (shunt capacitance of driver circuit in farads)
00410	C7 = (shunt capacitance of pickup circuit in farads)
00420	V0 = (output voltage in volts)
00430	G5 = (amplifier gain)
00440	F = (operating frequency in Hertz)
00450	L2 = (normalized lift-off increment of the driver coil)
00510	N9 = (total number of conductors + 1)
00520	N8 = (number of the specific conductor with a defect)
00540	DATA RHO/(resistivities in microhm-cm)/
00550	DATA U/(permeabilities)/
00560	DATA T/(thicknesses in inches)/

00580 R8 = (normalized defect distance from coil axis)

00590 Z7 = (defect distance below the surface of the N8-th layer in inches)

00600 V5 = (normalized defect volume)

00610 A1 = (shape and orientation factor of defect)

The current version of MULTID.F4 is limited to a maximum of nine conductors. However, this limitation can be removed easily by changing one DIMENSION statement:

```
00110    DIMENSION  T(N9), U(N9), RHO(N9), M(N9), BETA(N9) .
```

The print-out of the FORTRAN version of MULTID is practically identical to the BASIC version and will not be repeated. The main difference is that the question mark is not printed out when the program is ready to accept data. The Coil Design, Attenuator Design, Drift Check, and Continue Calculations options are the same. The line numbers, constant names, and parameter varied in the drift calculations are as follows:

Line Number	Constant	Parameter Varied
04380	DR1	Driver Resistance
04390	DR2	Pickup Resistance
04400	DR3	Driver Shunt Capacitance
04410	DR4	Pickup Shunt Capacitance
04420	DR5	Series Resistance
04430	DR6	Amplifier Input Resistance
04440	DR7	Applied Voltage
04450	DR8	Frequency
04460	DR9	Mean Radius

For example, to vary the driver resistance by 2% one would type:

```
04380    DR1 = 0.02
```

As in the BASIC version, the last two drifts require that the entire numerical integration be repeated and are relatively long running. If any of the drifts is set equal to zero, it will be omitted from the drift calculations.

Sample Calculation of MULTID.F4

Let us suppose that we wish to design a reflection-type coil, identical to the one designed by the BASIC version. We put the following data in the program (generally by using the EDIT MULTID.F4 command on the PDP-10 and inserting the statements). All linear dimensions are normalized by dividing by the coil mean radius, except the coil mean radius, which is in inches.

```
00250       R5 = .06
00260       R1 = .75
00270       R2 = 1.25
00280       L3 = .3
00290       R3 = .35
00300       R4 = .7
00310       L4 = .1
00320       L5 = 0.0
00330       L6 = .05
00340       R6 = 59.06
00350       R7 = 1067.4
00360       N3 = 252.0
00370       N4 = 450.0
00380       R0 = 1.0E6
00390       R9 = 1.0E6
00400       C6 = 1.0E-12
00410       C7 = 1.0E-12
00420       V0 = 10.0
00430       G5 = 1.0
00440       F = 1.0E5
00450       L2 = .0125
00510       N9 = 4
00520       N8 = 2
```

```
00540      DATA  RHO/130.0, 4.99, 75.0, 1.E10, 6*0.0/
00550      DATA  U/4*1.0, 6*0.0/
00560      DATA  T/1.E10, .01, .015, 1.0, 6*0.0/
00570      L7 = L3-2.0*(L4+L5)
00580      R8 = 1.0
00590      Z7 = .005
00600      V5 = 3.030811E-4
00610      A1 = 1.0
```

The FORTRAN program may now be executed. The print-out will be essentially identical to the BASIC print-out and will not be repeated. The FORTRAN version of MULTID follows.

```
C THIS PRØGRAM EVALUATES THE SENSITIVITY TØ A DEFECT
C LØCATED IN ANY GIVEN LAYER ØF A MULTI-LAYERED MATERIAL
      CØMPLEX BETAO,BETA1,BETA,V,TR,GAMMA1,GAMMA2,MUT
      CØMPLEX DRIVER,PICKUP,GH,IJ,EX
      CØMMØN X,Z,Q1,PI/B1/BETAO,BETA1
      CØMMØN /B2/R1,R2,R3,R4,L3,L4,RO,R6,R7,R9,C6,C7
      CØMMØN /B2/VO,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
      CØMMØN /B3/PICKUP,AIR1,AIR2/B4/GAGE,XIN,XØUT
      CØMMØN /B4/XLEN,TURNS,N1A,J1,PERLAY,XLAY
      CØMMØN /B3/GH,IJ/B5/V5,A1,DO
      DIMENSIØN T(10),U(10),RHØ(10),M(10),BETA(10)
      DIMENSIØN V(2,2),TR(2,2),DRIVER(5)
      DIMENSIØN PICKUP(5),RL(5),TMAG(5),PHASE(5)
      DIMENSIØN SHIFT(5),MUT(5),GH(5),IJ(5)
      REAL L2,L3,L4,L5,L6,L7,M,N3,N4
      PI=3.1415926536
      RAD=180.0/PI
C
C
C
C
      JKL=0
C THE FØLLØWING ARE INPUT DATA FØR THE PARAMETERS ØF THE
C CØIL,MATERIALS, AND CIRCUIT
      R5=.06
      R1=.75
      R2=1.25
      L3=.3
      R3=.35
      R4=.7
      L4=.1
      L5=0.0
      L6=.05
      R6=59.06
      R7=1067.4
      N3=252.0
      N4=450.0
      RO=1.0E6
      R9=1.0E6
      C6=1.0E-12
      C7=1.0E-12
      VO=10.0
      G5=1.0
      F=1.0E5
      L2=.0125
C N9 IS THE TØTAL NUMBER ØF LAYERS,INCLUDING THE CØIL
C ZØNE,AND N8 IS THE LAYER IN WHICH THE DEFECT IS LØCALED
C
C
C
      N9=4
      N8=2
      IF(N9.LT.2.ØR.N8.GE.N9) GØ TØ 1010
      DATA RHØ/130.0,4.99,75.0,1.E10,6*0.0/
      DATA U/4*1.0,6*0.0/
      DATA T/1.E10,.01,.015,1.0,6*0.0/
      L7=L3-2.0*(L4+L5)
      R8=1.0
```

```
      Z7=.005
      V5=3.030811E-4
      A1=1.0
    5 W=2.0*PI*F
      IF(JKL.NE.0) GØ TØ 15
C THE SYSTEM PARAMETERS ARE PRINTED ØUT
      TYPE 10
   10 FØRMAT(1H ,1X,1HN,13X,10HTHICK.(IN),4X,11HR(M-ØHM CM),
     1 3X,7HM,SIGMA,9X,1HU)
   15 DØ 50 I=1,N9
      IF(RHØ(I).GT.1.0E9) GØ TØ 20
      M(I)=0.5094*U(I)*F*R5*R5/RHØ(I)
      GØ TØ 25
   20 M(I)=0.0
   25 IF(JKL.NE.0) GØ TØ 50
   30 TYPE 40,I,T(I),RHØ(I),M(I),U(I)
   40 FØRMAT(1H ,I2,12X,1PE12.5,2X,E12.5,2X,E12.5,2X,0PF6.2)
   50 CØNTINUE
      T(N9)=0.0
      D0=6.0805E-2*F*R5*R5/RHØ(N8)
      IF(JKL.NE.0) GØ TØ 105
      TYPE 470
      TYPE 60,R1,R2,L3
   60 FØRMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
     1F8.5)
      TYPE 70,R3,R4,L4
   70 FØRMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
     1F8.5)
      TYPE 80,R5,F
   80 FØRMAT(1H ,17HCØIL MEAN RADIUS=,F8.5,7H INCHES,3X,
     120HØPERATING FREQUENCY=,1PE12.5)
      TYPE 90,L5
   90 FØRMAT(1H ,15HPICKUP RECESSED,F8.5)
      TYPE 100,L6,L2
  100 FØRMAT(1H ,13HMIN LIFT-ØFF=,F8.5,3X,19HLIFT-ØFF INCREM
     1ENT=,F8.5)
      R85=R8*R5
      TYPE 103,R85,Z7,N8
  103 FØRMAT(1H ,'DEFECT LØCATED AT R=',F9.6,' INCHES AND'/
     2 ' Z=',F9.6,' INCHES BELØW SURFACE ØF',I2,'TH LAYER')
C THE FIRST INTERVAL AND INCREMENT ØF THE INTEGRATIØN
C   ARE DEFINED
  105 S1=0.01
      S2=5.0
      B1=0.0
      B2=S2
      DØ 107 I=1,5
      MUT(I)=(0.0,0.0)
      GH(I)=(0.0,0.0)
      DRIVER(I)=(0.0,0.0)
      IJ(I)=(0.0,0.0)
  107 PICKUP(I)=(0.0,0.0)
      AIR1=0.0
      AIR2=0.0
  110 I1=(B2-B1)/S1
C THE INTEGRATIØN IS BY THE TRAPEZØIDAL METHØD, EVALUATING
C   AT THE CENTER ØF THE INCREMENTAL INTERVAL
      X=B1-S1/2.0
```

```
C THE INTEGRATION BEGINS HERE
      DØ 390 IDX=1,I1
      X=X+S1
      TEST=X*L3
      IF(TEST.GT.20.0) GØ TØ 120
      W3=EXP(-TEST)
      GØ TØ 130
  120 W3=0.0
  130 W8=1.0-W3
      TEST=X*L4
      IF(TEST.GT.20.0) GØ TØ 140
      W4=EXP(-TEST)
      GØ TØ 150
  140 W4=0.0
  150 W9=1.0-W4
      TEST=X*L7
      IF(TEST.GT.20.0) GØ TØ 160
      W7=EXP(-TEST)
      GØ TØ 170
  160 W7=0.0
  170 W5=EXP(-X*L5)
      W0=1.0-W7*W4
      TEST=X*L6
      IF(TEST.GT.20.0) GØ TØ 385
      W6=EXP(-TEST)
      Z=X*R2
      Q1=R2
      CALL BESSEL(VAL2)
      Z=X*R1
      Q1=R1
      CALL BESSEL(VAL1)
      Z=X*R4
      Q1=R4
      CALL BESSEL(VAL4)
      Z=X*R3
      Q1=R3
      CALL BESSEL(VAL3)
C RJ1=J1(X*R) IS CALCULATED
      ZS=X*R8
      IF(ZS.GT.3.0) GØ TØ 173
      Q1S=ZS*ZS
      Q2S=((2.1E-11*Q1S-5.38E-9)*Q1S+6.757E-7)*Q1S
     3 -5.42443E-5
      Q2S=((Q2S*Q1S+2.60415E-3)*Q1S-6.25E-2)*Q1S+0.5
      RJ1=ZS*Q2S
      GØ TØ 176
  173 Q3S=(((-.14604057/ZS+.27617679)/ZS-.20210391)
     4 /ZS+4.61835E-3)/ZS
      Q3S=((Q3S+.14937)/ZS+4.68E-6)/ZS+.79788456
      Q4S=(((-.21262014/ZS+.19397232)/ZS
     5 +6.022188E-2)/ZS-1.7222733E-1)/ZS
      Q4S=((Q4S+5.085E-4)/ZS+.37498836)/ZS-2.35619449+ZS
      RJ1=Q3S*CØS(Q4S)/SQRT(ZS)
  176 S3=S1*(VAL2-VAL1)*(VAL4-VAL3)
      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
      S6=S1*(VAL2-VAL1)*RJ1
      S7=S1*(VAL4-VAL3)*RJ1
```

```
      A5=W6*W6*W5*W8*W9*W0*S3
      A6=W6*W6*W8*W8*S4
      A7=W6*W6*W5*W5*W9*W9*W0*W0*S5
      A8=W6*W8*S6
      A9=W6*W9*W0*S7
C FØR X LARGE THE MATRIX CALCULATIØNS ARE BYPASSED
      IF(X.GT.30.0) GØ TØ 385
      QSUM=0.0
      N=N9
  180 IF(M(N).EQ.0.0) GØ TØ 190
      BETA(N)=CSQRT(CMPLX(X*X,M(N)))/U(N)
      GØ TØ 200
  190 BETA(N)=CMPLX(X,0.0)
  200 QSUM=QSUM+REAL(BETA(N))*T(N)/R5
      IF(QSUM.GT.20.0.ØR.N.EQ.1) GØ TØ 210
      N=N-1
      GØ TØ 180
  210 N7=N
      V(1,2)=BETA(N+1)-BETA(N)
      V(2,2)=BETA(N+1)+BETA(N)
      BETA0=BETA(N+1)
      IF(N8.LT.(N7+2)) GØ TØ 250
      N72=N7+2
      IF(N72.GT.N8) GØ TØ 250
      DØ 240 N=N72,N8
      BETA1=BETA(N)
      CALL XFØRM(N,TR,R5,U,T)
      JUMP=1
      CALL MATRIX(JUMP,V,TR,BETA1)
  240 BETA0=BETA1
  250 IF(N8.LT.(N7+1)) GØ TØ 270
      N=N8
      EX=CEXP(BETA(N)*(U(N)*(T(N)-Z7)/R5))
      V(1,1)=V(1,2)/EX+V(2,2)*EX
      IF(N8.LT.(N7+2)) GØ TØ 260
      N7=N8-1
  260 GØ TØ 290
  270 IF(N8.LT.N7) GØ TØ 280
      EX=CEXP(BETA(N)*U(N)*Z7/R5)
      V(1,1)=2.0*BETA(N+1)/EX
      GØ TØ 290
  280 V(1,1)=(0.0,0.0)
  290 N72=N7+2
      IF(N72.GT.N9) GØ TØ 302
      DØ 300 N=N72,N9
      BETA1=BETA(N)
      CALL XFØRM(N,TR,R5,U,T)
      JUMP=0
      CALL MATRIX(JUMP,V,TR,BETA1)
  300 BETA0=BETA1
  302 GAMMA1=V(1,2)/V(2,2)
      GAMMA2=V(1,1)/V(2,2)
      RL(1)=1.0
      TEST=X*L2
      IF(TEST.GT.20.0) GØ TØ 340
      W2=EXP(-TEST)
      GØ TØ 350
  340 W2=0.0
```

```
 350 DØ 370 K=2,5
     AK=K
     TEST=AK*X*L2
     IF(TEST.GT.20.0) GØ TØ 360
     RL(K)=W2*RL(K-1)
     GØ TØ 370
 360 RL(K)=0.0
 370 CØNTINUE
     DØ 380 K=1,5
     MUT(K)=MUT(K)+GAMMA1*RL(K)*RL(K)*A5
     DRIVER(K)=DRIVER(K)+GAMMA1*RL(K)*RL(K)*A6
     PICKUP(K)=PICKUP(K)+GAMMA1*RL(K)*RL(K)*A7
C GH AND IJ ARE THE CØRRECTIØNS TØ DRIVER AND PICKUP
C   IMPEDANCE DUE TØ THE DEFECT
     GH(K)=GH(K)+GAMMA2*RL(K)*A8
 380 IJ(K)=IJ(K)+GAMMA2*RL(K)*A9
 385 AIR1=AIR1+2.0*S4*(X*L3-W8)
     AIR2=AIR2+S5*(4.0*(X*L4-W9)-2.0*W7*W9*W9)
 390 CØNTINUE
C THE INTEGRATIØN ENDS; THE NEXT INTERVAL IS TAKEN
     B1=B2
     B2=B2+S2
C FØR X LARGE, THE INTEGRAL CØNVERGES FASTER, SØ
C   LARGER STEP SIZES ARE TAKEN
     S1=0.05
     IF(X.LT.9.0) GØ TØ 110
     S1=0.1
     IF(X.LT.29.0) GØ TØ 110
     S1=0.2
     IF(X.LT.39.0) GØ TØ 110
     S1=0.5
     IF(X.LT.79.0) GØ TØ 110
     IF(JKL.NE.0) GØ TØ 780
 400 QDFIND=0.0
     CALL CIRCT(TMAG,PHASE,Q0,T1,T2,QDFIND)
     CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
C THE RESULTS ARE PRINTED
     TYPE 410
 410 FØRMAT(1H ,10HDRIVER RES,4X,10HINDUCTANCE,4X,
    18HNØ TURNS,6X,9HSHUNT CAP,5X,9HNØR IM PT)
     Q1=Q0*T1*T1*AIR1/W
     Q2=(REAL(DRIVER(3))+AIR1)/AIR1
     Q3=Q0*T2*T2*AIR2/W
     Q4=(REAL(PICKUP(3))+AIR2)/AIR2
     TYPE 420,R6,Q1,N3,C6,Q2
 420 FØRMAT(1H ,1PE12.5,2X,E12.5,2X,0PF8.1,6X,1PE12.5,
    12X,0PF9.6)
     TYPE 430
 430 FØRMAT(1H ,10HPICKUP RES,4X,10HINDUCTANCE,4X,
    18HNØ TURNS,6X,9HSHUNT CAP,5X,9HNØR IM PT)
     TYPE 420,R7,Q3,N4,C7,Q4
     TYPE 440
 440 FØRMAT(1H ,12HDRIVING VØLT,2X,10HSERIES RES,4X,
    18HAMP GAIN,6X,9HINPUT IMP)
     TYPE 450,V0,R0,G5,R9
 450 FØRMAT(1H ,F5.1,9X,1PE12.5,2X,0PF8.1,6X,1PE12.5)
     TYPE 460,V1
 460 FØRMAT(1H ,22HDISCRIMINATØR VØLTAGE=,1PE12.5)
```

```
      TYPE 470
  470 FØRMAT(1H )
      RL(1)=L6
      DØ 480 I=2,5
  480 RL(I)=L2+RL(I-1)
      TYPE 490,RL
  490 FØRMAT(1H ,4(F6.3,8X),F6.3)
      TYPE 470
C THE VØLTAGE MAGNITUDE, PHASE, AND SHIFT ARE PRINTED
      TYPE 510,(TMAG(J),J=1,5)
      TYPE 510,(PHASE(J),J=1,5)
      TYPE 510,(SHIFT(J),J=1,5)
      TYPE 470
  510 FØRMAT(1H ,4(1PE12.5,2X),E12.5)
      CALL SENS(SHIFT,RAD)
C THE EFFECT ØF THE DEFECT IS DETERMINED
      QDFIND=V5*A1*D0
      CALL CIRCT(TMAG,PHASE,Q0,T1,T2,QDFIND)
      TYPE 513,V5,A1
  513 FØRMAT(1H ,'DEFECT VØL IS',1PE13.6,
     9 '  SHAPE AND ØRIENTATIØN FACTØR',E13.6)
      TYPE 470
      SEN=0.0
      DØ 516 J=1,5
      RM=TMAG(J)
      QPRINT=RAD*(SET-ATAN2(V1,SQRT(RM*RM-V1*V1))
     6 +PHASE(J)-SHIFT(J))
      SEN=SEN+QPRINT/RAD
  516 TYPE 518,QPRINT
  518 FØRMAT(1H+,1PE12.5,2X$)
      SEN=SEN/5.0
      TYPE 470
C THE USER IS ØFFERED THE ØPTIØN ØF MAKING VARIØUS
C   DESIGN CHANGES
  520 TYPE 530
  530 FØRMAT(1H ,'1 CØIL DESIGN  2 ATTEN. DESIGN  3 DRIFT CHECK
     1   4 CØN CAL')
      TYPE 470
      ACCEPT 540,N5
  540 FØRMAT(I1)
      GØ TØ(550,680,760,1010),N5
C IN THE FIRST PØSSIBILITY, USER ENTERS INTEGER DATA FØR
C   FØUR FACTØRS; ZERØ MEANS NØT CHANGED FRØM INITIAL VALUE
  550 TYPE 560
  560 FØRMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
     1 TURNS')
      TYPE 470
      ACCEPT 570,N1A,N2A,N3A,N4A
  570 FØRMAT(4I)
      IF(N1A*N2A.EQ.0) GØ TØ 580
      GAGE=N1A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      TURNS=N2A
      N3=N2A
      N1A=-1
      J1=1
```

```
      CALL GAGER(R6)
      GØ TØ 600
  580 IF(N1A.EQ.0) GØ TØ 590
      GAGE=N1A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=1
      CALL GAGER(R6)
      N3=TURNS
      GØ TØ 600
  590 IF(N2A.EQ.0) GØ TØ 620
      N3=N2A
      TURNS=N2A
      XIN=R1*R5
      XØUT=R2*R5
      XLEN=L3*R5
      J1=0
      CALL GAGER(R6)
  600 TYPE 610,TURNS,GAGE,PERLAY,XLAY,R6
  610 FØRMAT(1H ,6HDRIVER,F6.1,10H TURNS ØF#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  620 IF(N3A*N4A.EQ.0) GØ TØ 630
      GAGE=N3A
      TURNS=N4A
      N4=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      R7=2.0*R7
      GØ TØ 650
  630 IF(N3A.EQ.0) GØ TØ 640
      GAGE=N3A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=1
      CALL GAGER(R7)
      R7=2.0*R7
      N4=TURNS
      GØ TØ 650
  640 IF(N4A.EQ.0) GØ TØ 670
      N4=N4A
      TURNS=N4A
      XIN=R3*R5
      XØUT=R4*R5
      XLEN=L4*R5
      J1=0
      CALL GAGER(R7)
      R7=2.0*R7
  650 TYPE 660,TURNS,GAGE,PERLAY,XLAY,R7
  660 FØRMAT(1H ,6HPICKUP,F6.1,10H TURNS EA#,F5.1,4HWIRE,
     1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4HØHMS)
  670 GØ TØ 400
C THE SECØND PØSSIBILITY ACCEPTS E-FIELD DATA FØR FØUR
C   ØTHER PARAMETERS
```

```
  680 TYPE 690
  690 FØRMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
     1 SHUNT CAP')
      TYPE 470
      ACCEPT 700,P1,P2,P3,P4
  700 FØRMAT(4E)
      IF(P1.EQ.0.0) GØ TØ 710
      R0=P1
  710 IF(P2.EQ.0.0) GØ TØ 720
      C6=P2
  720 IF(P3.EQ.0.0) GØ TØ 730
      R9=P3
  730 IF(P4.EQ.0.0) GØ TØ 740
      C7=P4
  740 Q5=1.0/(W*SQRT(Q1*Q2*C6))
      Q6=SQRT(Q1*Q2/C6)
      Q7=R0/(W*Q1*Q2)
      Q8=1.0/(W*SQRT(Q3*Q4*C7))
      Q9=SQRT(Q3*Q4/C7)
      Q10=R9/(W*Q3*Q4)
      TYPE 750,Q5,Q6,Q7
  750 FØRMAT(1H ,7HDVR CKT,1PE12.5,10H BELØW RES,1PE12.5,
     18H ØPT RES,1PE12.5,11H RES/REACT.)
      TYPE 755,Q8,Q9,Q10
  755 FØRMAT(1H ,7HP-U CKT,1PE12.5,10H BELØW RES,1PE12.5,
     1 8H ØPT RES,1PE12.5,11H RES/REACT.)
      GØ TØ 400
C THE THIRD PØSSIBILITY EXAMINES THE EFFECTS ØF DRIFTS
C   ØN THE SYSTEM
  760 TYPE 770
  770 FØRMAT(1H ,23HSYSTEM DRIFT VARIATIØNS)
      DR1=0.01
      DR2=0.01
      DR3=0.01
      DR4=0.01
      DR5=0.01
      DR6=0.01
      DR7=0.01
      DR8=0.01
      DR9=0.01
      GØ TØ 790
  780 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      GØ TØ (970,1000),JKL
  790 TYPE 800
  800 FØRMAT(1H ,11H% VARIATIØN,3X,13HPARAMETER VAR,1X,
     17HRADIANS,7X,7HDEGREES,7X,10H% ØF RANGE)
      IF(DR1.EQ.0.0) GØ TØ 830
      R6=R6*(1.0+DR1)
      DR100=100.0*DR1
      TYPE 820,DR100
  820 FØRMAT(1H ,F4.1,10X,13HDRIVER RES    $)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R6=R6/(1.0+DR1)
  830 IF(DR2.EQ.0.0) GØ TØ 850
      R7=R7*(1.0+DR2)
      DR100=100.0*DR2
      TYPE 840,DR100
  840 FØRMAT(1H ,F4.1,10X,13HPICKUP RES    $)
```

```
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R7=R7/(1.0+DR2)
  850 IF(DR3.EQ.0.0) GØ TØ 870
      C6=C6*(1.0+DR3)
      DR100=100.0*DR3
      TYPE 860,DR100
  860 FØRMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      C6=C6/(1.0+DR3)
  870 IF(DR4.EQ.0.0) GØ TØ 890
      C7=C7*(1.0+DR4)
      DR100=100.0*DR4
      TYPE 880,DR100
  880 FØRMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      C7=C7/(1.0+DR4)
  890 IF(DR5.EQ.0.0) GØ TØ 910
      R0=R0*(1.0+DR5)
      DR100=100.0*DR5
      TYPE 900,DR100
  900 FØRMAT(1H ,F4.1,10X,13HSERIES RES    $)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R0=R0/(1.0+DR5)
  910 IF(DR6.EQ.0.0) GØ TØ 930
      R9=R9*(1.0+DR6)
      DR100=100.0*DR6
      TYPE 920,DR100
  920 FØRMAT(1H ,F4.1,10X,13HAMP INPUT RES$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      R9=R9/(1.0+DR6)
  930 IF(DR7.EQ.0.0) GØ TØ 950
      V0=V0*(1.0+DR7)
      DR100=100.0*DR7
      TYPE 940,DR100
  940 FØRMAT(1H ,F4.1,10X,13HAPPLIED VØLT.$)
      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
      V0=V0/(1.0+DR7)
  950 IF(DR8.EQ.0.0) GØ TØ 980
      F=F*(1.0+DR8)
      DR100=100.0*DR8
      TYPE 960,DR100
  960 FØRMAT(1H ,F4.1,10X,13HFREQUENCY    $)
      JKL=1
      GØ TØ 5
  970 F=F/(1.0+DR8)
      JKL=0
  980 IF(DR9.EQ.0.0) GØ TØ 520
      R5=R5*(1.0+DR9)
      DR100=100.0*DR9
      TYPE 990,DR100
  990 FØRMAT(1H ,F4.1,10X,13HMEAN RADIUS  $)
      JKL=2
      GØ TØ 5
 1000 R5=R5/(1.0+DR9)
      JKL=0
      GØ TØ 520
C THE FØURTH PØSSIBILITY ENDS CALCULATIØNS
 1010 CALL EXIT
```

```
      END
      SUBRØUTINE BESSEL(VAL)
      CØMMØN X,Z,Q1,PI
      IF(Z.GT.5.0) GØ TØ 1510
      L=2.0*Z+3.0
      F1=0.5*Q1*Q1*Q1
      VAL=F1/3.0
      DØ 1500 I=1,L
      AI=I
      F1=-F1*0.25*Z*Z/(AI*AI+AI)
 1500 VAL=VAL+F1/(2.0*AI+3.0)
      GØ TØ 1520
 1510 X0=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
      X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
      X1=(((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
      X1=(X1-0.187344E-2)/Z+0.7979095
      VAL=(1.0-SQRT(Z)*(X1*CØS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
     1(X*X*X)
 1520 RETURN
      END
      SUBRØUTINE XFØRM(N,TR,R5,U,T)
      CØMMØN /B1/BETA0,BETA1
      CØMPLEX BETA0,BETA1,EX,TR
      DIMENSIØN EX(2),U(10).T(10),TR(2,2)
      EX(1)=CEXP(-BETA0*U(N-1)*T(N-1)/R5)
      EX(2)=1.0/EX(1)
      DØ 1610 I=1,2
      DØ 1610 J=1,2
      K=I+J
      IF(K.EQ.3) GØ TØ 1600
      TR(I,J)=(BETA1+BETA0)*EX(J)
      GØ TØ 1610
 1600 TR(I,J)=(BETA1-BETA0)*EX(J)
 1610 CØNTINUE
      RETURN
      END
      SUBRØUTINE MATRIX(JUMP,V,TR,BETA1)
      CØMPLEX V,Q,TR,BETA1
      DIMENSIØN Q(2,2),V(2,2),TR(2,2)
      IF(JUMP.EQ.1) GØ TØ 1720
      Q(1,1)=V(1,1)
      V(1,1)=2.0*BETA1*Q(1,1)
 1720 DØ 1730 I=1,2
 1730 Q(I,2)=V(I,2)
      DØ 1740 I=1,2
      V(I,2)=(0.0,0.0)
      DØ 1740 J=1,2
 1740 V(I,2)=V(I,2)+TR(I,J)*Q(J,2)
      RETURN
      END
      SUBRØUTINE CIRCT(TMAG,PHASE,Q0,T1,T2,Q)
      CØMPLEX MUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
      CØMPLEX DENØM,TNUM,VØLT,GH,IJ
      CØMMØN /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
      CØMMØN /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
      CØMMØN /B3/PICKUP,AIR1,AIR2,GH,IJ
      DIMENSIØN MUT(5),DRIVER(5),PICKUP(5)
      DIMENSIØN TMAG(5),PHASE(5),GH(5),IJ(5)
```

```
      REAL L3,L4,N3,N4
      T1=N3/((R2-R1)*L3)
      T2=N4/((R4-R3)*L4)
      Q0=6.300475204E-7*F*R5
      Z1=CMPLX(W*R0*C6,-1.0)
      Z2=CMPLX(W*R9*C7,-1.0)
      Z3=CMPLX(0.0,-R0)
      Z4=CMPLX(0.0,-R9)
      DØ 1800 J=1,5
      Z5=Q0*T1*T2*(MUT(J)+Q*(0.0,-1.0)*GH(J)*IJ(J))
      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(J)+AIR1+Q*GH(J)*GH(J))
      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(J)+AIR2+Q*IJ(J)*IJ(J))
      DENØM=Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*(Z2*(Z7+R7)+Z4)
      TNUM=V0*R9*G5*(0.0,-1.0)*Z5
      VØLT=TNUM/DENØM
      TMAG(J)=CABS(VØLT)
 1800 PHASE(J)=ATAN2(AIMAG(VØLT),REAL(VØLT))
      RETURN
      END
      SUBRØUTINE PHASET(A,B,C,V1,Ø3)
      DIMENSIØN A(5),B(5),C(5)
      Ø1=A(5)*SIN(B(5))-A(1)*SIN(B(1))
      Ø2=-(A(5)*CØS(B(5))-A(1)*CØS(B(1)))
      Ø3=ATAN2(Ø1,Ø2)
      V1=A(1)*SIN(Ø3+B(1))
      DØ 1900 J=1,5
 1900 C(J)=Ø3-ATAN2(V1,SQRT(A(J)*A(J)-V1*V1))+B(J)
      RETURN
      END
      SUBRØUTINE SENS(Ø,RAD)
      DIMENSIØN Ø(5)
      Q2=0.0
      DØ 2000 J=1,5
      Q1=Ø(J)
      IF(ABS(Q2).GT.ABS(Q1)) GØ TØ 2000
      Q2=Q1
 2000 CØNTINUE
      Q2DEG=Q2*RAD
      TYPE 2010,Q2,Q2DEG
 2010 FØRMAT(1H ,'LIFT-ØFF=',1PE13.6,' RADIANS ØR',
     6 E13.6,' DEGREES')
      RETURN
      END
      SUBRØUTINE GAGER(RES)
      CØMMØN /B4/G,D1,D2,RLN,T5,N1A,J1,D,E
      PI=3.1415926536
      IF(J1.EQ.1) GØ TØ 2120
      N1A=-1
      D3=0.95*SQRT((D2-D1)*RLN/T5)
      X2=1.0371E-5/(D3*D3)
      Q=40.0
 2100 G=40.0+10.0*(ALØG(X2)-ALØG(.9989+.017*(Q/10.0-1.0)))/2.3
     10259
      IF(ABS(Q-G).LT.1.0E-4) GØ TØ 2110
      Q=G
      GØ TØ 2100
```

```
2110 IG=G
     G=IG
2120 X2=(.9989+.017*(G/10.0-1.0))*10.0**(G/10.0-4.0)
     D3=SQRT(1.0371E-5/X2)
     IF(G.GT.40.0) GØ TØ 2130
     X3=(.460655*ALØG(D3*1.0E3)-.43444)*1.0E-3
     GØ TØ 2140
2130 X3=(98.02228*D3+2.56791E-2)*1.0E-3
2140 ID=(RLN/(D3+X3))
     D=ID
     IE=(D2-D1)/(D3+X3)
     E=IE
     IF(N1A.EQ.-1) GØ TØ 2150
     T5=D*E
2150 RES=T5*X2*(D2+D1)*PI/12.0
     RETURN
     END
     SUBRØUTINE CIRCT1(Ø1,V1,Ø,RAD,SEN)
     CØMMØN /B5/V5,A1,D0
     DIMENSIØN Ø(5),TMAG(5),PHASE(5)
     QDFIND=V5*A1*D0
     CALL CIRCT(TMAG,PHASE,Q0,T1,T2,QDFIND)
     Q1=0.0
     DØ 2200 J=1,5
     Q2=Ø1-ATAN2(V1,SQRT(TMAG(J)*TMAG(J)-V1*V1))
    1+PHASE(J)-Ø(J)
     IF(ABS(Q1).GT.ABS(Q2)) GØ TØ 2200
     Q1=Q2
2200 CØNTINUE
     Q2NEW=RAD*Q1
     Q3=100.0*Q1/SEN
     TYPE 2210,Q1,Q2NEW,Q3
2210 FØRMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
     RETURN
     END
```

SUMMARY AND CONCLUSIONS

The theoretical analysis and computer programs to study eddy-current problems using reflection type coils are given in this report. The results of these analyses will agree quite well with experimental results, with errors on the order of 1% when the coils are large enough to be accurately fabricated. In general, the conductivity and thickness calculations are more accurate than the defect calculations. These programs allow highly accurate, complete, and rapid design of optimum solution to eddy-current problems without the necessity of fabricating standards or making experimental measurements and avoid expensive trial-and-error approaches that have less than optimum results.

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