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## THE ANALYSIS OF REFLECTION TYPE COILS FOR EDDY-CURRENT TESTING

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METALS AND CERAMICS DIVISION

THE ANALYSIS OF REFLECTION TYPE COILS FOR EDDY-CURRENT TESTING

C. V. Dodd, C. C. Cheng, W. A. Simpson, D. A. Deeds, and J. H. Smith

APRIL 1973

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## THE ANALYSIS OF REFLECTION TYPE COILS FOR EDDY-CURRENT TESTING

C. V. Dodd, C. C. Cheng,<sup>1</sup> W. A. Simpson, D. A. Deeds,<sup>2</sup> 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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<sup>2</sup>Summer student from the University of Tennessee.

voltage.<sup>3,4</sup> 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<sup>5,6</sup> 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

<sup>3</sup>R. Hochschild, "Electromagnetic Methods of Testing Metals," *Progress in Nondestructive Testing*, Vol. I, The Macmillan Company, New York, 1959.

<sup>4</sup>R. C. McMaster, *Nondestructive Testing Handbook*, Vol. II, The Ronald Press Co., 1959.

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

<sup>6</sup>C. V. Dodd, "A Portable Phase-Sensitive Eddy-Current Instrument," *Mater. Eval.* 26(3): 33-36 (March 1968).

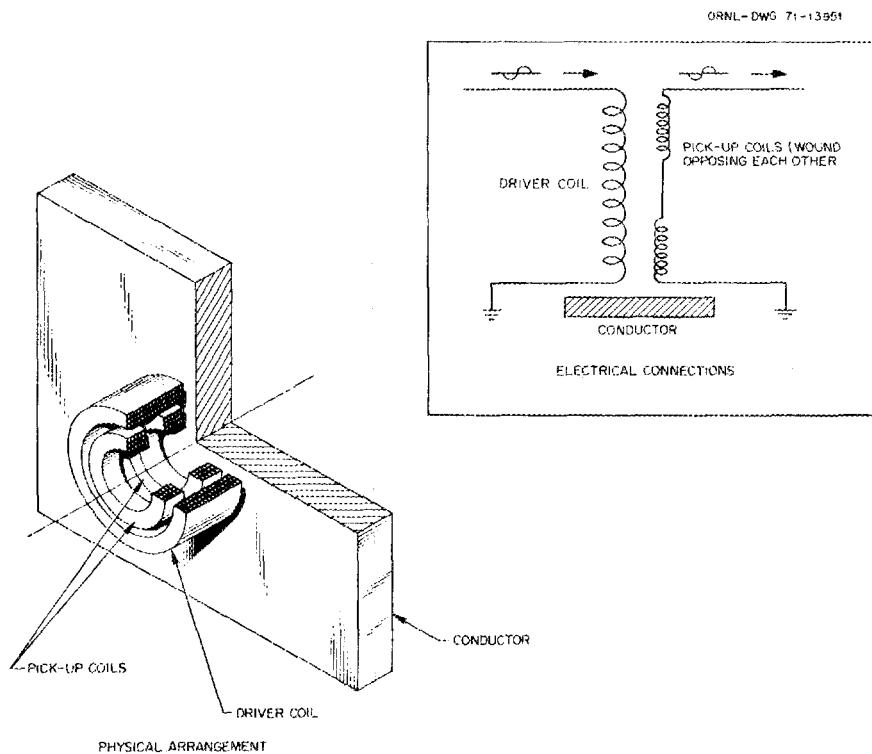


Fig. 1. A Reflection-Type Probe in the Presence of a Conductor.

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:

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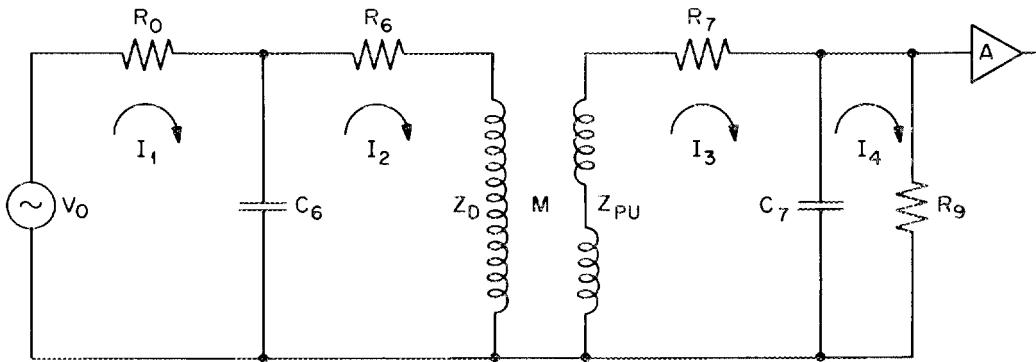
 $V_0$  DRIVING VOLTAGE $R_0$  SERIES RESISTANCE IN THE DRIVING CIRCUIT $C_6$  SHUNT CAPACITANCE OF THE DRIVING CIRCUIT $R_6$  D.C. RESISTANCE OF THE DRIVER COIL $Z_D$  IMPEDANCE OF THE DRIVER COIL $M$  MUTUAL IMPEDANCE BETWEEN THE DRIVER AND PICK-UP COILS $Z_{PU}$  IMPEDANCE OF THE PICK-UP COILS $R_7$  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  $\omega$  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  $V_0$ :

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

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.

$$V_{out} = -j \frac{MV_0R_9G}{\omega C_6 C_7} \div \left\{ \left( R_o - \frac{j}{\omega C_6} \right) \omega^2 M^2 \left( R_9 - \frac{j}{\omega C_7} \right) + \left[ \left( R_o - \frac{j}{\omega C_6} \right) \left( Z_D + R_6 - \frac{j}{\omega C_6} \right) + \frac{1}{\omega^2 C_6^2} \right] \left[ \left( R_9 - \frac{j}{\omega C_7} \right) \left( Z_{PU} + R_7 - \frac{j}{\omega C_7} \right) + \frac{1}{\omega^2 C_7^2} \right] \right\} \quad (6)$$

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<sup>7</sup> for the voltage induced in a pickup coil by a current  $I_1$  flowing in a driver coil, as shown in Fig. 3.

$$V = j\omega I_1 \pi n n' \mu_0 \int_0^\infty \frac{1}{\alpha^6} J(r_2, r_1) J(r_4, r_3) \left\{ 2\alpha(\ell'_2 - \ell'_1) + \right. \\ \left. [1 - e^{-\alpha(\ell'_2 - \ell'_1)}] \cdot [\gamma \left( e^{-\alpha(\ell_1 + \ell'_1)} - e^{-\alpha(\ell_2 + \ell'_1)} \right) - e^{-\alpha(\ell_2 - \ell'_2)} - e^{-\alpha(\ell'_1 - \ell_1)}] \right\} da \quad (7)$$

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 ( $\ell'_2$  must not be greater than  $\ell_2$  and  $\ell'_1$  must not be less than  $\ell_1$ ). The  $\gamma$  factor is a function of the metal alone and is more fully explained in ref. 7. The function  $J(r_2, r_1)$  is

$$\int_{ar_1}^{ar_2} x J_1(x) dx ,$$

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  $\theta$  direction for one coil and the negative  $\theta$  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

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<sup>7</sup>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).

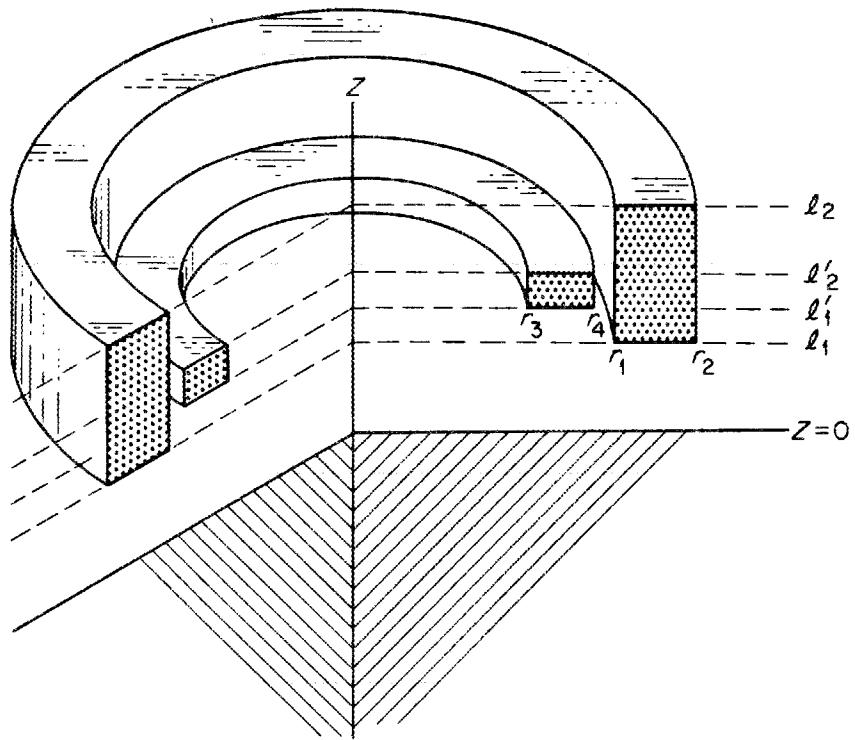


Fig. 3. Driver Coil Encircling a Pickup Coil.

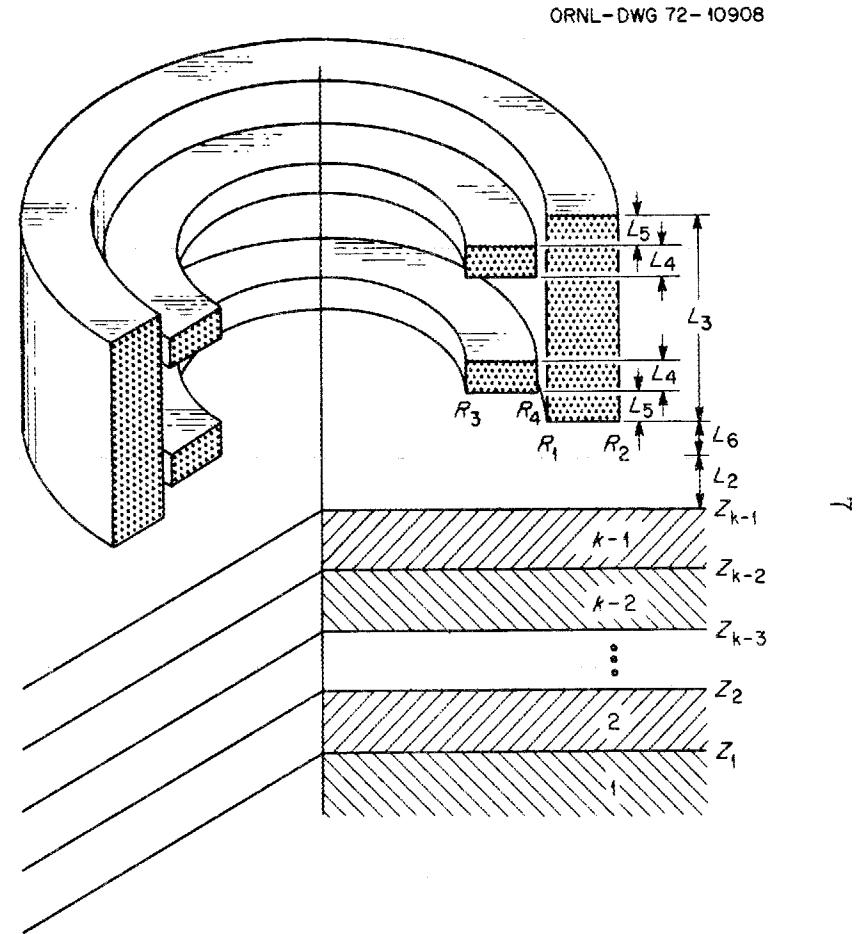


Fig. 4. Reflection Probe Above Multiple Conductors.

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

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

$$M = \frac{\pi N_3 N_4 \mu_0 R_5}{L_3(R_2-R_1)L_4(R_4-R_3)} \int_0^{\infty} \frac{1}{\alpha^6} J(R_2, R_1) J(R_4, R_3) e^{-\alpha L_5} e^{-2\alpha L_2} e^{-2\alpha L_6} \\ \left( 1 - e^{-\alpha L_4} \right) \left( 1 - e^{-\alpha L_3} \right) \left( 1 - e^{-\alpha(L_3-L_4-2L_5)} \right) \gamma d\alpha \quad (8)$$

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  $\alpha$ '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

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

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

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

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

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

However  $\vec{l}_2$  is in the opposite direction from our normal direction of integration. Performing the dot product and integrating in the  $+0$  direction gives:

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

Calculating the impedance of both coils gives

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

This equation is the same as

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

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,

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

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

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

For the rear pickup we have

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

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

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

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<sup>8</sup> per unit current in a pickup coil due to the presence of a flaw is:

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

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

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<sup>8</sup>C. V. Dodd, W. E. Deeds, J. W. Luquaire, 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

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

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

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

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

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

(continued on next page)

$$\times \left\{ \frac{N_4}{(R_4 - R_3)L_3} \int_0^\infty \frac{e^{-\alpha(L_2 + L_6 + L_5)}}{\alpha^3} \left[ 1 - e^{-\alpha(L_3 - L_4 - 2L_5)} \right] J(R_4, R_3) \left[ 1 - e^{-\alpha L_4} \right] \right. \\ \left. \times \left[ J_1(\alpha r) \left( \frac{V_{12}(n,1)}{V_{22}(k,1)} e^{-\alpha_n z} + \frac{V_{22}(n,1)}{V_{22}(k,1)} e^{\alpha_n z} \right) \right] d\alpha \right\} = j\omega M' .$$

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

$$\frac{V_{12}(n,1)}{V_{22}(k,1)} = 2^{k-n} e^{-(-1)^\ell \alpha_n z} \frac{V_{12}(n,1)}{V_{22}(k,1)} \left\{ \beta_{n+1} \beta_{n+2} \dots \beta_k \right\} . \quad (22)$$

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

$$V_{12}(1,1) = V_{12}(1,1) = \begin{cases} 0 & \text{if } \ell = 1 \\ 1 & \text{if } \ell = 2 \end{cases} .$$

Therefore,

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

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

$$v'_{12}(2,1) \equiv \left[ \beta_2 + (-1)^i \beta_1 \right] = t_{12}(2,1) \text{ for } i = 1, 2 , \quad (24)$$

where

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

and is dimensionless. The  $\mu_n$  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

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

(3) From this we shall numerically calculate:

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

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

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

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

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

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

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

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

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

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

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

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

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

If we have two conductors, the  $\gamma$  factor becomes:

$$\begin{aligned} \frac{V_{12}(3,1)}{V_{22}(3,1)} &= \frac{t_{11}(3,2)V_{12}(2,1) + t_{12}(3,2)V_{22}(2,1)}{t_{21}(3,2)V_{12}(2,1) + t_{22}(3,2)V_{22}(2,1)} \\ &= \frac{(\beta_3 + \beta_2)(\beta_2 - \beta_1)e^{-\alpha_2(z_2 - z_1)} + (\beta_3 - \beta_2)(\beta_2 + \beta_1)e^{+\alpha_2(z_2 - z_1)}}{(\beta_3 - \beta_2)(\beta_2 - \beta_1)e^{-\alpha_2(z_2 - z_1)} + (\beta_3 + \beta_2)(\beta_2 + \beta_1)e^{+\alpha_2(z_2 - z_1)}}. \end{aligned} \quad (33)$$

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

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

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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<sup>9</sup>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  $\bar{r}^2\omega\mu_0$  at which the minimum lift-off effect occurs. In general, in order to make the value of  $\bar{r}^2\omega\mu_0$  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  $\bar{r}^2\omega\mu_0$  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 R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, and R<sub>4</sub> 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  $\omega$  to  $\omega_0$  (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  $\omega$  to the first power. The ratio of the resonant frequency to the operating frequency is given by

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

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  $\omega_0/\omega$  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:

$$\text{Min Inductance} \approx \frac{R_0 \text{ min}}{1.5 Im \left[ \omega_{\text{min}} \left( \frac{\omega_0}{\omega_{\text{min}}} \right) \right]} . \quad (37)$$

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

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

where  $\omega$  is the minimum operating frequency under consideration and  $\omega_0/\omega_{\min}$  is the ratio of the resonance frequency to the minimum frequency.

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

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

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

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

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  $\omega_0/\omega$  must be selected (for each value of operating frequency). This is given by

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

and the ratio  $\omega_0/\omega$  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

$$R_0 \approx 1.25 \omega L_D \left( \frac{\omega_0}{\omega} \right) \quad (42)$$

for the driver series resistance ( $R_0$ ), and

$$R_9 \approx 1.75 \omega L_{PU} \left( \frac{\omega_0}{\omega} \right) \quad (43)$$

for the pickup shunt resistance ( $R_9$ ). 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  $R_0$  and  $R_9$  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  $R_0$  and  $R_9$  so that several calculations on each may be necessary. Drifts on the order of  $0.005^\circ/\text{ }^\circ\text{C}$  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  $\tilde{r}^2 \omega \mu_0$  at which the minimum lift-off error occurs, it is desirable to design the coil without an attenuator so that the value of  $\tilde{r}^2 \omega \mu_0$  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  $\tilde{r}^2 \omega \mu_0$  for minimum lift-off error increases as the ratio  $\omega_0/\omega$  decreases for a particular coil. The value of  $\tilde{r}^2 \omega \mu_0$

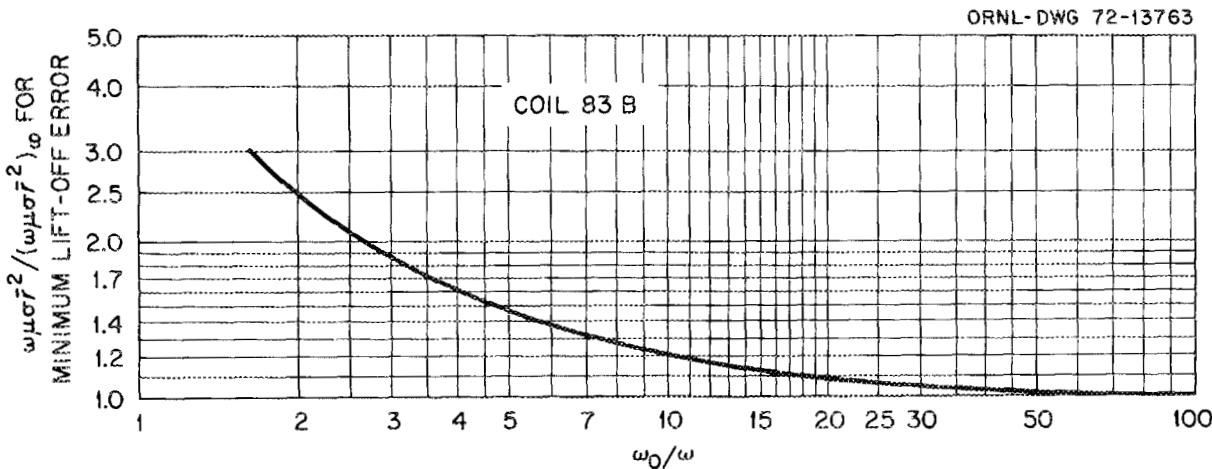


Fig. 5. Ratio of the Value of  $\bar{r}^2 \omega \mu \sigma$  for Minimum Lift-Off Error for an Attenuator Having a Resonant to Operating Frequency of  $\omega_0 / \omega$  to the value of  $\bar{r}^2 \omega \mu \sigma_\infty$  for Minimum Lift-Off Error with an Infinite Ratio of  $\omega_0 / \omega$ , Plotted Against  $\omega_0 / \omega$ .

for minimum lift-off error with an infinite ratio of  $\omega_0 / \omega$  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      Kl = (numerical value of resistivity of conductor in microhm
           centimeter)
515      Ul = (numerical value of relative permeability of conductor)
750      MO = (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)				
Ul= (Ul)	M1= .....	RESISTIVITY= (Kl) MICROHM CM		
TOTAL CONDUCTIVITY VARIATION ABS (200.MO)%				
DRIVER RES (R6)	INDUCTANCE .....	NO TURNS (N3) SHUNT CAP (C6) NOR IM PT .....		
PICKUP RES (R7)	INDUCTANCE .....	NO TURNS SHUNT CAP (C7) NOR IM PT .....		
DRIVING VOLT (VO)	SERIES RES (R8)	AMP GAIN (G5) INPUT IMP (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 %) 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 V0, the output voltage of the driving amplifier. The value of the dimensionless product  $R_s^2 \omega \mu_1 \sigma_1$  is also calculated and printed out as  $M_1 = (R_s^2 \omega \mu_1 \sigma_1)$ . 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 ( $L_6+2L_2$ ), 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\*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,  $R_0$ , the driver shunt capacitance,  $C_6$ , the amplifier input impedance,  $R_9$ , and the shunt capacitance in the pickup circuit,  $C_7$ , 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:

<u>Parameter</u>	<u>Line Number</u>	<u>Constant</u>
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  $\Omega$ , and the pickup coils have 2925 turns each of No. 48 wire, with a resistance of 3443.01  $\Omega$  for both coils. The input resistances of both the driver series and the pickup amplifier are chosen to be 1 M $\Omega$ . 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 0.030 in. with a lift-off increment of 0.0075 in. The nominal resistivity of the material is 2.95  $\mu\Omega$  cm, the variation in conductivity is  $\pm 5\%$ , 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.

## RFCON(BASIC)

R1= 0.75      R2= 1.25      DRIVER LENGTH IS 0.6  
 R3= 0.35      R4= 0.7      PICK UP LENGTH IS 0.2  
 COIL MEAN RADIUS 0.3 INCHES      OPERATING FREQUENCY 500  
 PICK UP RECESSED 0  
 MIN LIFT-OFF= 0.1 LIFT-OFF INCREMENT= 0.025  
 U1= 1      M1= 7.77051      RESISTIVITY= 2.95 MICROHM CM  
 TOTAL CONDUCTIVITY VARIATION 10 %  
 DRIVER RES      INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT  
   57.555      9.60145E-3      810      1.00000E-12      0.879034  
 PICKUP RES      INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT  
   3443.01      8.83174E-2      2925      1.00000E-12      0.991484  
 DRIVING VOLT      SERIES RES      AMP GAIN      INPUT IMP  
   10      1000000      1      1000000  
 DISCRIMINATOR VOLTAGE 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-OFF 5.08092E-4 % 1.70464				
DEGREE 1.70778      2.91116E-2				
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?1</u>				

DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS

?36,0,48,0

DRIVER 924 TURNS OF # 36 WIRE 33 /LAYER 28 LAYERS 60.2723 OHM  
 PICKUP 3225 TURNS EA # 48 WIRE 43 /LAYER 75 LAYERS 3569.24 OHMS TOTAL  
 DRIVER RES      INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT  
   60.2723      1.24943E-2      924      1.00000E-12      0.879034  
 PICKUP RES      INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT  
   3569.24      0.107363      3225      1.00000E-12      0.991484  
 DRIVING VOLT      SERIES RES      AMP GAIN      INPUT IMP  
   10      1000000      1      1000000

## DISCRIMINATOR VOLTAGE 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-OFF 5.08152E-4 % 1.70484				
DEGREE 1.70778 2.91150E-2				
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?2</u>				

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	BELOW RES 302.529	OPT RES 11.8828	RES/REACTANCE	
P-U CT 9.30217	BELOW RES 3110.81	OPT RES 16.1475	RES/REACTANCE	
DRIVER RES	INDUCTANCE	NØ TURNS	SHUNT CAP	
60.2723	1.24943E-2	924	NØR IM PT 1.20000E-7 0.879034	
PICKUP RES	INDUCTANCE	NØ TURNS	SHUNT CAP	
3569.24	0.107363	3225	NØR IM PT 1.10000E-8 0.991484	
DRIVING VOLT	SERIES RES	AMP GAIN	INPUT IMP	
10	410	1	5400	
DISCRIMINATOR VOLTAGE 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-OFF 7.48619E-4 % 2.52719				
DEGREE 1.69725 4.28928E-2				
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?3</u>				

SYSTEM DRIFT VARIATIONS				
% VARIATN	PARAMETER	RADIAN	DEGREE	% OF 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 VOLT	-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 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?4</u>				

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 RFC0N(BASIC)
10 REM REFLECTION COIL ON A SINGLE CONDUCTOR
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=.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 CONDUCTOR DATA
500 DIM K(3),N(3),L(5)
510 K1=2.95
515 U1=1
520 G0 SUB 600
540 G0 T0 750
599 REM SUBROUTINE FOR 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 COIL DATA
1000 PRINT "R1=";R1;"R2=";R2;"DRIVER LENGTH IS";L3
1010 PRINT "R3=";R3;"R4=";R4;"PICK UP LENGTH IS";L4
1020 PRINT "COIL MEAN RADIUS";R5;"INCHES      OPERATING FREQUENCY";F
1030 PRINT "PICK UP RECESSED";L5
1040 PRINT "MIN LIFT-OFF=";L6;"LIFT-OFF INCREMENT=";L2
1050 PRINT "U1=";U1;"M1=";M1;"RESISTIVITY=";K1;"MICROHM CM"
1060 PRINT "TOTAL CONDUCTIVITY VARIATION";200*ABS(M0);"%"
1100 REM PROGRAM BEGINS
1110 REM FOR INTEGRATIONS
1120 G0 SUB 1500
1130 REM FOR INDUCTANCES AND CIRCUITS MAGNITUDE AND PHASE

```

```
1140 G0 SUB 6000
1150 REM FØR DISCRIMINATOR VOLTAGE AND PHASE SHIFT
1160 G0 SUB 6500
1170 REM FØR PRINTING OF RESULTS
1180 G0 SUB 6700
1190 REM FØR AV. PHASE SHIFT AND LIFT-OFF ERROR
1200 G0 SUB 7000
1400 REM FØR COIL AND ATTENUATOR DESIGNS, AND DRIFT
1410 G0 T0 7200
1499 REM SUBROUTINE FØR INTEGRATION
1500 A3=0
1510 A4=0
1520 FOR I=1 TO 3
1530 FOR J=1 TO 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=S
1650 S1=1E-2
1660 FOR X=B1+S1/2 TO B2 STEP S1
1670 G0 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 SUBROUTINE FØR L-FACTOR AND INTEGRANTS
1999 REM FØR J-FACTOR
2000 G0 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 FOR J=2 TO 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 FOR GAMMA FACTOR
2330 G0 SUB 3200
2340 FOR I=1 TO 3
2350 FOR J=1 TO 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 SUBROUTINE FOR JS=J(R1,R2)/X^3, J6=J(R3,R4)/X^3
2700 R=R1
2710 G0 SUB 2900
2720 J1=02
2730 R=R2
2740 G0 SUB 2900
2750 J5=02-J1
2760 R=R3
2770 G0 SUB 2900
2780 J3=02
2790 R=R4
2800 G0 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 SUBROUTINE FOR 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

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2940 Q3=INT(2*Z)+3
2950 FOR Q=1 TO Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 GO TO 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+COS(Z-P9/4))-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3198 REM SUBROUTINE FOR GAMMA FACTOR(K(I),N(I))
3199 REM AND BETA(X1,Y1)
3200 Q1=X*X
3210 Q2=Q1*Q1
3220 FOR I=1 TO 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 SUBROUTINE FOR 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 FOR I=1 TO 3
6080 FOR J=1 TO 5
6090Z8=Q0*N1*N2*A(I,J)
6100Z9=Q0*N1*N2*B(I,J)
6110Z7=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

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```

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 SUBROUTINE FOR DISC. VOLTAGE AND PHASE SHIFT
6500 Q1=M(2,5)*SIN(P(2,5))-M(2,1)*SIN(P(2,1))
6510 Q2=-M(2,5)*COS(P(2,5))+M(2,1)*COS(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 Q1=Q3
6556 Q2=V1
6560 FOR I=1 TO 3
6570 FOR J=1 TO 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 SUBROUTINE FOR PRINTING RESULTS
6700 PRINT "DRIVER RES", "INDUCTANCE", "NO TURNS", "SHUNT CAP", "NOR IM PT"
6710 PRINT R6, 00*N1*N1*A3/W, N3, C6, (D(2,3)+A3)/A3
6720 PRINT "PICKUP RES", "INDUCTANCE", "NO TURNS", "SHUNT CAP", "NOR IM PT"
6730 PRINT R7, Q0*N2*N2*A4/W, N4, C7, (F(2,3)+A4)/A4
6740 PRINT "DRIVING VOLT", "SERIES RES", "AMP GAIN", "INPUT IMP"
6750 PRINT V0, R0, G5, R9
6760 PRINT "DISCRIMINATOR VOLTAGE IS"; V1
6770 PRINT
6780 PRINT L6, L6+L2, L6+2*L2, L6+3*L2, L6+4*L2
6790 FOR I=1 TO 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 SUBROUTINE FOR AV. PHASE SHIFT AND LIFT-OFF ERROR
7000 Q1=Q(1,1)
7010 Q2=Q(1,1)
7020 FOR J=2 TO 5
7030 IF Q(I,J)<Q1 THEN 7050
7040 Q1=Q(I,J)
7050 IF Q(I,J)>Q2 THEN 7070
7060 Q2=Q(I,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 Q=Q
7100 PRINT "PHASE SHIFT"; Q; "LIFT-OFF"; Q1-Q2; "%"; 100*(Q1-Q2)/Q
7110 PRINT "DEGREE"; Q*P8, (Q1-Q2)*P8
7120 RETURN
7199 REM FOR COIL DESIGN, ATTENUATOR, DRIFT, AND EXIT
7200 PRINT "1 COIL DESIGN 2 ATTN. DESIGN 3 DRIFT CHECK 4 CON CAL"
7210 INPUT N5

```

```

7220PRINT
72300N NS GO TO 7300,8200,8600,9900
7299 REM FOR COIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FOR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 G0 SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER";N3;"TURNS OF #";G;"WIRE";
7390 PRINT Q7;"/LAYER";Q8;"LAYERS";R6;"0HM"
7399 REM FOR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
7430 W2=R4
7440 W3=L4
7450 G0 SUB 7510
7460 N4=Q2
7470 R7=2*Q9
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIRE";
7490 PRINT Q7;"/LAYER";Q8;"LAYERS";R7;"0HMS TOTAL"
7500 G0 TO 1140
7509 REM SUBROUTINE FOR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FOR 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*(LOG(Q6)-LOG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 G0 TO 7590
7630 G=INT(G)
7639 REM FOR 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*LOG(Q5*1E3)-.43444)*1E-3+Q5
7680 G0 TO 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 FOR ATTENUATOR 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));"BELOW RES";
8330 PRINT SQR(Q1/C6);"OPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELOW RES";
8350 PRINT SQR(Q2/C7);"OPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 G0 T0 1140
8599 REM FOR DRIFTS
8600 PRINT "SYSTEM DRIFT VARIATIONS"
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","% OF RANGE"
8720 IF E1=0 THEN 8770
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 G0 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 G0 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 G0 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 G0 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 G0 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 G0 SUB 9320
9010 R9=R9/(1+E8)

```

```
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VOLT",
9050 G0 SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 G0 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 G0 SUB 9300
9160 R5=R5/(1+A2)
9170 IF A8=0 THEN 9220
9180 K1=K1*(1+A8)
9190 PRINT 100*A8,"RESISTIVITY",
9200 G0 SUB 9300
9210 K1=K1/(1+A8)
9220 G0 T0 7200
9299 REM SUBROUTINE FOR DRIFT
9300 G0 SUB 600
9310 G0 SUB 1500
9320 G0 SUB 6000
9330 Q1=0
9340 FOR I=1 TO 3
9350 FOR J=1 TO 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*Q1/0
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      RH01 = (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:

<u>Line Number</u>	<u>Constant</u>	<u>Parameter Varied</u>
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	RH01 = 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.

```

00010C IN THIS PROGRAM, RH01 IS THE RESISTIVITY
00020C SIGMA IS THE GAMMA FACTOR
00030      COMPLEX BETA1,BETA2,EX1,RNUM,DEN,SIGMA
00040      COMPLEX TMUT,DRIVER,PICKUP
00050      REAL L3,L4,L5,L6,L2,N3,N4,M9,M9A,K1
00060      COMMON X,Z,Q1,PI/B1/R1,R2,R3,R4,L3,L4,R0,R6,R7
00070      COMMON /B1/R9,C6,C7,V0,GAIN,W,FREQ,R5,N3,N4
00080      COMMON /B2/TMUT,DRIVER,PICKUP,AIR1,AIR2/B3/GAGE,XIN
00090      COMMON /B3/XOUT,XLEN,TURNS,NIA,J1,PERLAY,XLAY
00100      DIMENSION RL(5),SIGMA(3),TMUT(3,5),DRIVER(3,5)
00110      DIMENSION PICKUP(3,5),TMAG(3,5),PHASE(3,5),SHIFT(3,5)
00120      EQUIVALENCE (RH01,K1),(GAIN,G5),(FREQ,F)
00130      PI=3.14159265
00140      RAD=180.0/PI
00150C
00160C
00170C
00180C
00190C
00200C
00210C
00220      JKL=0
00230C THE FOLLOWING ARE INPUT DATA FOR THE PARAMETERS OF
00240C THE COILS, MATERIAL, AND CIRCUIT
00250      R5=.3
00260      R1=.75
00270      R2=1.25
00280      L3=.6
00290      R3=.35
00300      R4=.7
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=1.0E6
00390      R9=1.0E6
00400      C6=1.0E-12
00410      C7=1.0E-12
00420      V0=10.0
00430      GAIN=1.0
00440      FREQ=500.0
00450      L2=0.025
00460      RH01=2.95
00470      U1=1.0
00480      M9=.05
00490      M9A=200.0*M9
00500      5 W=2.0*PI*FREQ
00510      RM1=0.5094*U1*FREQ*R5*R5/RH01
00520C THE SYSTEM PARAMETERS ARE PRINTED OUT
00530      IF(JKL.NE.0) GO TO 105
00540      TYPE 30,R1,R2,L3
00550      30 FORMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14H DRIVER LENGTH=,
00560      1F8.5)
00570      TYPE 40,R3,R4,L4

```

```

00580 40 F0RFORMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
00590   1F8.5)
00600   TYPE 50,R5,FREQ
00610 50 F0RFORMAT(1H ,17HC0IL MEAN RADIUS=,F8.5,7H INCHES,3X,
00620   120H0PERATING FREQUENCY=,1PE12.5)
00630   TYPE 60,L5
00640 60 F0RFORMAT(1H ,15HPICKUP RECESSED,F8.5)
00650   TYPE 70,L6,L2
00660 70 F0RFORMAT(1H ,13HMIN LIFT-OFF=,F8.5,3X,19HLIFT-OFF INCREMENT=
00670   1F8.5)
00680   TYPE 80,U1,RM1,RH01
00690 80 F0RFORMAT(1H ,3HU1=,F6.2,5X,3HM1=,F9.5,2X,12HRESISTIVITY=,
00700   11PE12.5,11H MICR0HM CM)
00710   TYPE 90,M9A
00720 90 F0RFORMAT(1H ,23HC0NDUCTIVITY VARIATION=, F8.2,1HZ)
00730C THE INTEGRATION IS PERFORMED BY THE TRAPEZOIDAL METHOD,
00740C EVALUATING AT THE CENTER OF THE INTERVAL; FOR X LARGE
00750C THE INTEGRAL CONVERGES RAPIDLY, SO LARGER INTERVALS
00760C ARE TAKEN
00770C IN THE INTEGRATION TMUT, DRIVER, PICKUP, AIR1, AND
00780C AIR2 ARE CALCULATED
00790 105 S1=0.01
00800   S2=5.0
00810   B1=0.0
00820   B2=S2
00830   AIR1=0.0
00840   AIR2=0.0
00850   D0 108 J=1,3
00860   D0 108 K=1,5
00870   DRIVER(J,K)=(0.0,0.0)
00880   PICKUP(J,K)=(0.0,0.0)
00890   TMUT(J,K)=(0.0,0.0)
00900 108 C0NTINUE
00910 110 I1=(B2-B1)/S1
00920   X=B1-S1/2.0
00930   D0 170 M=1,I1
00940   X=X+S1
00950   Z=R2*X
00960   Q1=R2
00970C SUBROUTINE BESSEL EVALUATES THE INTEGRAL OF
00980C THE PRODUCT OF THE BESSEL FUNCTION AND ITS
00990C ARGUMENT
01000   CALL BESSEL(VAL2)
01010   Z=R1*X
01020   Q1=R1
01030   CALL BESSEL(VAL1)
01040   Z=R4*X
01050   Q1=R4
01060   CALL BESSEL(VAL4)
01070   Z=R3*X
01080   Q1=R3
01090   CALL BESSEL(VAL3)
01100   S3=S1*(VAL4-VAL3)*(VAL2-VAL1)
01110   S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
01120   S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
01130   EX3=EXP(-X*L3)
01140   W1=1.0-EX3
01150   EX4=EXP(-X*L4)

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01160      W2=1.0-EX4
01170      EX5=EXP(-X*L5)
01180      W3=EX3/(EX4*EX4*EX5*EX5)
01190      IF(X.GT.30.0) GO TO 160
01200C FROM HERE THROUGH LINE 130, SIGMA IS CALCULATED
01210      D0 130 I=1,3
01220      RI=I-2
01230      RM=RM1*(1.0+RI*M9)
01240      BETA1=CSORT(CMPLX(X*X,RM))/UJ
01250 120 SIGMA(I)=(X-BETA1)/(X+BETA1)
01260 130 CONTINUE
01270      EX2=EXP(-2.0*X*L2)
01280      EX6=EXP(-2.0*X*L6)
01290      W4=1.0-EX4*W3
01300      W5=EX5*EX6*W1*W2*W4
01310      W6=EX6*W1*W1
01320      W7=W2*W2*EX6*EX5*EX5*W4*W4
01330      RL(1)=1.0
01340      D0 140 K=2,5
01350 140 RL(K)=EX2*RL(K-1)
01360      D0 150 K=1,3
01370      D0 150 L=1,5
01380      TMUT(K,L)=TMUT(K,L)+S3*W5*RL(L)*SIGMA(K)
01390      DRIVER(K,L)=DRIVER(K,L)+S4*W6*RL(L)*SIGMA(K)
01400 150 PICKUP(K,L)=PICKUP(K,L)+S5*W7*RL(L)*SIGMA(K)
01410 160 AIR1=AIR1+S4*2.0*(X*L3-W1)
01420      AIR2=AIR2+S5*(4.0*(X*L4-W2)-2.0*W2*W2*W3)
01430 170 CONTINUE
01440      B1=B2
01450      B2=B2+S2
01460      S1=0.05
01470      IF(X.LT.9.0) GO TO 110
01480      S1=0.1
01490      IF(X.LT.29.0) GO TO 110
01500      S1=0.2
01510      IF(X.LT.39.0) GO TO 110
01520      S1=0.5
01530      IF(X.LT.79.0) GO TO 110
01540C THE INTEGRATION ENDS HERE
01550      IF(JKL.NE.0) GO TO 552
01560C NEXT THE PROPERTIES OF THE COILS ARE DETERMINED AND PRINTED
01570 180 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
01580      CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
01590      TYPE 190
01600 190 FORMAT(1H ,10H DRIVER RES,4X,10H INDUCTANCE,4X,8HN0 TURNS,
01610      16X,9H SHUNT CAP,5X,9HN0R IM PT)
01620      Q1=Q0*T1*T1*AIR1/W
01630      Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
01640      Q3=Q0*T2*T2*AIR2/W
01650      Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
01660      TYPE 200,R6,Q1,N3,C6,Q2
01670 200 FORMAT(1H ,1PE12.5,2X,1PE12.5,2X,0PF8.1,6X,1PE12.5,2X,
01680      10PF9.6)
01690      TYPE 210
01700 210 FORMAT(1H ,10HPICKUP RES,4X,10H INDUCTANCE,4X,8HN0 TURNS,
01710      16X,9H SHUNT CAP,5X,9HN0R IM PT)
01720      TYPE 200,R7,Q3,N4,C7,Q4

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01730      TYPE 220
01740 220 FØRFORMAT(1H ,12HDRIVING VOLT,2X,10HSERIES RES,4X,
01750      18HAMP GAIN,6X,9HINPUT IMP)
01760      TYPE 230,VO,RO,GAIN,R9
01770 230 FØRFORMAT(1H ,F5.1,9X,1PE12.5,2X,OPF8.1,6X,1PE12.5)
01780      TYPE 240,V1
01790 240 FØRFORMAT(1H ,22HDISCRIMINATOR VOLTAGE=,1PE12.5)
01800      TYPE 250
01810 250 FØRFORMAT(1H )
01820      RL(1)=L6
01830      D0 260 I=2,5
01840 260 RL(1)=L2+RL(I-1)
01850      TYPE 270,RL
01860 270 FØRFORMAT(1H ,4(F6.3,8X),F6.3)
01870      TYPE 250
01880C THE VOLTAGE MAGNITUDE,PHASE,AND SHIFT ARE PRINTED FOR
01890C THE VARIOUS LIFT-OFF VALUES
01900      D0 280 I=1,3
01910      TYPE 290,(TMAG(I,J),J=1,5)
01920      TYPE 290,(PHASE(I,J),J=1,5)
01930      TYPE 290,(SHIFT(I,J),J=1,5)
01940      TYPE 250
01950 280 CØNTINUE
01960 290 FØRFORMAT(1H ,4(1PE12.5,2X),1PE12.5)
01970      CALL SENS(SHIFT,RAD,SEN)
01980C THE USER SELECTS ONE OF FOUR POSSIBILITIES
01990 295 TYPE 300
02000 300 FØRFORMAT(' 1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK
02010      1 4 CØN CAL')
02020      TYPE 250
02030      ACCEPT 310,N5
02040 310 FØRFORMAT(I1)
02050      G0 T0(320,450,540,690),N5
02060C THE FIRST POSSIBILITY PRINTS FACTORS IN THE COIL
02070C DESIGN; USER INPUTS INTEGER DATA AS REQUESTED
02080 320 TYPE 330
02090 330 FØRFORMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
02100      1PTURNS')
02110      TYPE 250
02120      ACCEPT 340,N1A,N2A,N3A,N4A
02130 340 FØRFORMAT(4I)
02140      IF (N1A*N2A.EQ.0) G0 T0 350
02150      GAGE=N1A
02160      XIN=R1*R5
02170      XOUT=R2*R5
02180      XLEN=L3*R5
02190      TURNS=N2A
02200      N3=N2A
02210      N1A=-1
02220      J1=1
02230      CALL GAGER(R6)
02240      G0 T0 370
02250 350 IF(N1A.EQ.0) G0 T0 360
02260      GAGE=N1A
02270      XIN=R1*R5
02280      XOUT=R2*R5
02290      XLEN=L3*R5
02300      J1=1

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```

02310      CALL GAGER(R6)
02320      N3=TURNs
02330      G0 T0 370
02340      360 IF(N2A.EQ.0) G0 T0 390
02350      N3=N2A
02360      TURNs=N2A
02370      XIN=R1*R5
02380      XOUT=R2*R5
02390      XLEN=L3*R5
02400      J1=0
02410      CALL GAGER(R6)
02420      370 TYPE 380,TURNs,GAGE,PERLAY,XLAY,R6
02430      380 FORMAT(1H ,6HDRIVER,F6.1,10H TURNs 0F#,F5.1,4HWIRE,
02440      1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
02450      390 IF(N3A*N4A.EQ.0) G0 T0 400
02460      GAGE=N3A
02470      TURNs=N4A
02480      N4=N4A
02490      XIN=R3*R5
02500      XOUT=R4*R5
02510      XLEN=L4*R5
02520      J1=1
02530      CALL GAGER(R7)
02540      R7=2.0*R7
02550      G0 T0 420
02560      400 IF(N3A.EQ.0) G0 T0 410
02570      GAGE=N3A
02580      XIN=R3*R5
02590      XOUT=R4*R5
02600      XLEN=L4*R5
02610      J1=1
02620      CALL GAGER(R7)
02630      N4=TURNs
02640      R7=2.0*R7
02650      G0 T0 420
02660      410 IF(N4A.EQ.0) G0 T0 440
02670      N4=N4A
02680      TURNs=N4A
02690      XIN=R3*R5
02700      XOUT=R4*R5
02710      XLEN=L4*R5
02720      J1=0
02730      CALL GAGER(R7)
02740      R7=2.0*R7
02750      420 TYPE 430,TURNs,GAGE,PERLAY,XLAY,R7
02760      430 FORMAT(1H ,6HPICKUP,F6.1,10H TURNs EA#,F5.1,4HWIRE,
02770      1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
02780      440 G0 T0 180
02790C THE SECOND POSSIBILITY DEALS WITH ATTENUATOR DESIGNS
02800C USER INPUTS REQUESTED DATA IN E FIELD TYPE
02810      450 TYPE 460
02820      460 FORMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
02830      1 SHUNT CAP')
02840      TYPE 250
02850      ACCEPT 470,P1,P2,P3,P4
02860      470 FORMAT(4E)
02870      IF(P1.EQ.0.0) G0 T0 480
02880      R0=P1

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```

02890 480 IF(P2.EQ.0.0) G0 T0 490
02900 C6=P2
02910 490 IF(P3.EQ.0.0) G0 T0 500
02920 R9=P3
02930 500 IF(P4.EQ.0.0) G0 T0 510
02940 C7=P4
02950 510 Q5=1.0/(W*SQRT(Q1*Q2*C6))
02960 Q6=SQRT(Q1*Q2/C6)
02970 Q7=R0/(W*Q1*Q2)
02980 Q8=1.0/(W*SQRT(Q3*Q4*C7))
02990 Q9=SQRT(Q3*Q4/C7)
03000 Q10=R9/(W*Q3*Q4)
03010 TYPE 520,Q5,Q6,Q7
03020 520 F0RMA7H,DVR CKT,1PE12.5,10H BELOW RES,1PE12.5,
03030 18H OPT RES,1PE12.5,11H RES/REACT.)
03040 TYPE 530,Q8,Q9,Q10
03050 530 F0RMA7H,HP-U CKT,1PE12.5,10H BELOW RES,1PE12.5,
03060 18H OPT RES,1PE12.5,11H RES/REACT.)
03070 G0 T0 180
03080C THE THIRD POSSIBILITY EXAMINES THE EFFECTS OF DRIFT
03090C ON THE SYSTEM
03100 540 TYPE 550
03110 550 F0RMA1H,23H SYSTEM DRIFT VARIATIONS)
03120 DR1=0.01
03130 DR2=0.01
03140 DR3=0.01
03150 DR4=0.01
03160 DR5=0.01
03170 DR6=0.01
03180 DR7=0.01
03190 DR8=0.01
03200 DR9=0.01
03210 DR10=0.01
03220 G0 T0 559
03230 552 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03240 G0 T0 (675,678,681), JKL
03250 559 TYPE 560
03260 560 F0RMA1H,11HZ VARIATION,3X,13H PARAMETER VAR,1X,
03270 17HRADIANS,7X,7HDEGREES,7X,10% OF RANGE)
03280 IF(DR1.EQ.0.0) G0 T0 580
03290 R6=R6*(1.0+DR1)
03300 DR100=100.0*DR1
03310 TYPE 570,DR100
03320 570 F0RMA1H,F4.1,10X,13H DRIVER RES $)
03330 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03340 R6=R6/(1.0+DR1)
03350 580 IF(DR2.EQ.0.0) G0 T0 600
03360 R7=R7*(1.0+DR2)
03370 DR100=100.0*DR2
03380 TYPE 590,DR100
03390 590 F0RMA1H,F4.1,10X,13H PICKUP RES $)
03400 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03410 R7=R7/(1.0+DR2)
03420 600 IF(DR3.EQ.0.0) G0 T0 620
03430 C6=C6*(1.0+DR3)
03440 DR100=100.0*DR3
03450 TYPE 610,DR100
03460 610 F0RMA1H,F4.1,10X,13H DVR SHUNT CAP$)

```

```

03470      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03480      C6=C6/(1.0+DR3)
03490  620 IF(DR4.EQ.0.0) G0 T0 640
03500      C7=C7*(1.0+DR4)
03510      DR100=100.0*DR4
03520      TYPE 630,DR100
03530  630 F0RMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
03540      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03550      C7=C7/(1.0+DR4)
03560  640 IF(DR5.EQ.0.0) G0 T0 660
03570      R0=R0*(1.0+DR5)
03580      DR100=100.0*DR5
03590      TYPE 650,DR100
03600  650 F0RMAT(1H ,F4.1,10X,13HSERIES RES   $)
03610      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03620      R0=R0/(1.0+DR5)
03630  660 IF(DR6.EQ.0.0) G0 T0 671
03640      R9=R9*(1.0+DR6)
03650      DR100=100.0*DR6
03660      TYPE 670,DR100
03670  670 F0RMAT(1H ,F4.1,10X,13HAMP INPUT RES$)
03680      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03690      R9=R9/(1.0+DR6)
03700  671 IF(DR7.EQ.0.0) G0 T0 673
03710      V0=V0*(1.0+DR7)
03720      DR100=100.0*DR7
03730      TYPE 672,DR100
03740  672 F0RMAT(1H ,F4.1,10X,13HAPPLIED VOLT.$)
03750      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03760      V0=V0/(1.0+DR7)
03770  673 IF(DR8.EQ.0.0) G0 T0 676
03780      FRE0=FREQ*(1.0+DR8)
03790      DR100=100.0*DR8
03800      TYPE 674,DR100
03810  674 F0RMAT(1H ,F4.1,10X,13HFREQUENCY     $)
03820      JKL=1
03830      G0 T0 5
03840  675 FRE0=FREQ/(1.0+DR8)
03850      JKL=0
03860  676 IF(DR9.EQ.0.0) G0 T0 679
03870      R5=R5*(1.0+DR9)
03880      DR100=100.0*DR9
03890      TYPE 677,DR100
03900  677 F0RMAT(1H ,F4.1,10X,13HMEAN RADIUS   $)
03910      JKL=2
03920      G0 T0 5
03930  678 R5=R5/(1.0+DR9)
03940      JKL=0
03950  679 IF(DR10.EQ.0.0) G0 T0 295
03960      RH01=RH01*(1.0+DR10)
03970      DR100=100.0*DR10
03980      TYPE 680,DR100
03990  680 F0RMAT(1H ,F4.1,10X,13HRESISTIVITY  $)
04000      JKL=3
04010      G0 T0 5
04020  681 RH01=RH01/(1.0+DR10)
04030      JKL=0
04040      G0 T0 295

```

```

04050C THE FOURTH POSSIBILITY ENDS CALCULATIONS
04060 690 CALL EXIT
04070 END
04080 SUBROUTINE BESEL(VAL)
04090 COMMON X,Z,Q1,PI
04100 IF(Z.GT.5.0) GO TO 1010
04110 K=2.0*Z
04120 L=K+3
04130 F1=0.5*Q1*Q1*Q1
04140 VAL=F1/3.0
04150 DO 1000 I=1,L
04160 AI=I
04170 F1=-F1*0.25*Z*Z/(AI*AI+AI)
04180 VAL=VAL+F1/(2.0*AI+3.0)
04190 1000 CONTINUE
04200 GO TO 1020
04210 1010 X0=((((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
04220 X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
04230 X1=((((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
04240 X1=(X1-0.187344E-2)/Z+0.7979095
04250 VAL=(1.0-SQRT(Z)*(X1*COS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
04260 1(X*X*X)
04270 1020 RETURN
04280 END
04290 SUBROUTINE PHASET(A,B,C,V1,03)
04300 DIMENSION A(3,5),B(3,5),C(3,5)
04310 01=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
04320 02=-(A(2,5)*COS(B(2,5))-A(2,1)*COS(B(2,1)))
04330 03=ATAN2(01,02)
04340 V1=A(2,1)*SIN(03+B(2,1))
04350 DO 2000 I=1,3
04360 DO 2000 J=1,5
04370 2000 C(I,J)=03-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(I,J)
04380 RETURN
04390 END
04400 SUBROUTINE SENS(0,RAD,01)
04410 DIMENSION 0(3,5)
04420 09=0(1,1)
04430 00=0(1,1)
04440 DO 3010 I=2,5
04450 IF(0(1,1).LT.09) GO TO 3000
04460 09=0(1,1)
04470 3000 IF(0(1,1).GT.00) GO TO 3010
04480 00=0(1,1)
04490 3010 CONTINUE
04500 01=(0(1,1)+0(1,2)+0(1,3)+0(1,4)+0(1,5))/5.0
04510 01=01-(0(3,1)+0(3,2)+0(3,3)+0(3,4)+0(3,5))/5.0
04520 XL0=09-00
04530 PERCT=100*XL0/01
04540 DEGR1=01*RAD
04550 DEGR2=XL0*RAD
04560 TYPE 3020,01,XL0,PERCT
04570 3020 FORMAT(1H ,12HPHASE SHIFT:,1PE12.5,2X,8HLIFTOFF=,
04580 11PE12.5,2X,2H%:,1PE12.5)
04590 TYPE 3030,DEGR1,DEGR2
04600 3030 FORMAT(1H ,7HDEGREE:,1PE13.5,5X,1PE13.5)
04610 RETURN
04620 END

```

```

04630      SUBROUTINE GAGER(RES)
04640      COMMON /B3/G,D1,D2,RLN,T5,N1,J1,D,E
04650      PI=3.1415926536
04660      IF(J1.EQ.1) GO TO 4015
04670      N1=-1
04680      D3=0.95*SQRT((D2-D1)*RLN/T5)
04690      X2=1.0371E-5/(D3*D3)
04700      Q=40.0
04710 4000  G=40.0+10.0*(ALOG(X2)-ALOG(.9989+.017*(Q/10.0-1.0)))/2.3
04720      10259
04730      IF(ABS(Q-G).LT.1.0E-4) GO TO 4010
04740      Q=G
04750      GO TO 4000
04760 4010  IG=G
04770      G=IG
04780 4015  X2=(.9989+.017*(G/10.0-1.0))*10.0**((G/10.0-4.0)
04790      D3=SQRT(1.0371E-5/X2)
04800      IF(G.GT.40.0) GO TO 4020
04810      X3=(-.460655*ALOG(D3*1.E3)-.43444)*1.E-3
04820      GO TO 4030
04830 4020  X3=(98.02228*D3+2.56791E-2)*1.E-3
04840 4030  ID=(RLN/(D3+X3))
04850      D=ID
04860      IE=(D2-D1)/(D3+X3)
04870      E=IE
04880      IF(N1.EQ.-1) GO TO 4040
04890      T5=D*E
04900 4040  RES=T5*X2*(D2+D1)*PI/12.0
04910      RETURN
04920      END
04930      SUBROUTINE CIRCT(TMAG,PHASE,Q0,T1,T2)
04940      COMMON /B1/R1,R2,R3,R4,RL3,RL4,R0,R6,R7,R9,C6,C7,V0,GAIN
04950      COMMON /B1/W,FREQ,RBAR,TURN1,TURN2/B2/TMUT,DRIVER
04960      COMMON /B2/PICKUP,AIR1,AIR2
04970      COMPLEX TMUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
04980      COMPLEX DENOM,TNUM,VOLT
04990      DIMENSION TMUT(3,5),DRIVER(3,5),PICKUP(3,5)
05000      DIMENSION TMAG(3,5),PHASE(3,5)
05010      T1=TURN1/((R2-R1)*RL3)
05020      T2=TURN2/((R4-R3)*RL4)
05030      Q0=6.300475204E-7*FREQ*RBAR
05040      Z1=CMPLX(W*R0*C6,-1.0)
05050      Z2=CMPLX(W*R9*C7,-1.0)
05060      Z3=CMPLX(0.0,-R0)
05070      Z4=CMPLX(0.0,-R9)
05080      D0 5000 I=1,3
05090      D0 5000 J=1,5
05100      Z5=Q0*T1*T2*TMUT(I,J)
05110      Z6=Q0*T1*T2*(0.0,1.0)*(DRIVER(I,J)+AIR1)
05120      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
05130      DENOM=Z1*Z2*Z5*Z6+(Z1*(Z6+R6)+Z3)*
05140      3 (Z2*(Z7+R7)+Z4)
05150      TNUM=V0*R9*GAIN*(0.0,-1.0)*Z5
05160      VOLT=TNUM/DENOM
05170      TMAG(I,J)=CABS(VOLT)
05180 5000  PHASE(I,J)=ATAN2(AIMAG(VOLT),REAL(VOLT))
05190      RETURN

```

```
05200      END
05210      SUBROUTINE CIRCT1(01,V1,0,RAD,SEN)
05220      DIMENSION 0(3,5),TMAG(3,5),PHASE(3,5)
05230      CALL CIRCT(TMAG,PHASE,00,T1,T2)
05240      Q1=0.0
05250      D0 6000 I=1,3
05260      D0 6000 J=1,5
05270      Q2=01-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
05280      1+PHASE(I,J)-0(I,J)
05290      IF(ABS(01).GT.ABS(Q2)) G0 T0 6000
05300      Q1=Q2
05310 6000  C0NTINUE
05320      02NEW=RAD*Q1
05330      Q3=100.0*01/SEN
05340      TYPE 6010,Q1,Q2NEW,Q3
05350 6010  F0RMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
05360      RETURN
05370      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 (R6)	INDUCTANCE .....	NO TURNS (N3)	SHUNT CAP (C6)	NOR IM PT .....
PICKUP RES (R7)	INDUCTANCE .....	NO TURNS (N4)	SHUNT CAP (C7)	NOR IM PT .....
DRIVING VOLT (VO)	SERIES RES (R0)	AMP GAIN (G5)	INPUT IMP (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 V<sub>O</sub>, the output voltage of the driving amplifier. The value of the dimensionless product  $R_s^2 \omega \mu_1 \sigma_1$  is also calculated and printed out as M<sub>1</sub> = ( $R_s^2 \omega \mu_1 \sigma_1$ ) and likewise M<sub>2</sub> is calculated using  $R_s^2 \omega \mu_2 \sigma_2$ . 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 (L<sub>6</sub>+2L<sub>2</sub>). 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<sub>DR</sub>, and Z<sub>PU</sub> 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:

<u>Parameter</u>	<u>Line Number</u>	<u>Constant</u>
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  $3.632 \mu\Omega\text{-cm}$  clad on aluminum with a resistivity of  $5.393 \mu\Omega\text{-cm}$ . From another report<sup>10</sup> 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  $79.36 \Omega$ , and the pickup coils have 410 turns each of No. 54 wire, with a resistance of  $530.5 \Omega$  for both coils. The driver series and the pickup amplifier input resistances are both chosen to be  $1 M\Omega$ . 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 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.

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<sup>10</sup>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  
 C0IL MEAN RADIUS 8.32500E-2 INCHES      OPERATING FREQUENCY 10000  
 PICK UP RECESSED 0  
 MIN LIFT-OFF= 0.1 LIFT-OFF INCREMENT= 0.025  
 U1= 1      M1= 6.54632      RESISTIVITY= 5.393 MICRΩHM CM  
 U2= 1      M2= 9.72034      RESISTIVITY= 3.632 MICRΩHM CM  
 THICKNESS= 0.0266      0.028      0.0294  
 DRIVER RES      INDUCTANCE      NO TURNS      SHUNT CAP      N0R IM PT  
   79.36      6.05067E-4      360      1.00000E-12      0.849616  
 PICKUP RES      INDUCTANCE      NO TURNS      SHUNT CAP      N0R IM PT  
   530.5      4.72124E-4      410      1.00000E-12      0.992308  
 DRIVING VOLT      SERIES RES      AMP GAIN      INPUT IMP  
   10      1000000      1      1000000  
 DISCRIMINATOR VOLTAGE 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-OFF 2.32607E-4 IN % 3.44404					
IN DEGREE 0.386971      1.33274E-2					
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL					
<u>?1</u>					

## 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 OHM  
 PICKUP 429 TURNS EA # 54 WIRE 11 /LAYER 39 LAYERS 532.582 OHMS TOTAL  
 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 VOLT SERIES RES AMP GAIN INPUT IMP  
 10 1000000 1 1000000  
 DISCRIMINATOR VOLTAGE 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-0FF 2.32592E-4 IN % 3.44382				
IN DEGREE 0.386971 1.33266E-2				
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON 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 BELOW RES 359.202 OPT RES 13.6474 RES/REACTANCE

P-U CT 9.6529 BELOW RES 311.091 OPT RES 18.3072 RES/REACTANCE

DRIVER RES	INDUCTANCE	NO TURNS	SHUNT CAP	NOR IM PT
71.9293	7.13760E-4	391	4.70000E-9	0.849616
PICKUP RES	INDUCTANCE	NO TURNS	SHUNT CAP	NOR IM PT
532.582	5.16896E-4	429	5.30000E-9	0.992308
DRIVING VOLT	SERIES RES	AMP GAIN	INPUT IMP	
10	520	1	590	

DISCRIMINATOR VOLTAGE 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-OFF 1.32054E-4 IN % 1.96905

IN DEGREE 0.384255 7.56615E-3

1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL

3

#### SYSTEM DRIFT VARIATIONS

% VARIATN	PARAMETER	RADIAN	DEGREE	% OF 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 VOLT	-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 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON 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 REFLECTION COIL FOR 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 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 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 G0 SUB 600
590 G0 T0 1000
599 REM SUBROUTINE FOR 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 COIL DATA
1000 PRINT "R1=";R1;"R2=";R2;"DRIVER LENGTH IS";L3
1010 PRINT "R3=";R3;"R4=";R4;"PICK UP LENGTH IS";L4
1020 PRINT "COIL MEAN RADIUS";RS;"INCHES      OPERATING FREQUENCY";F

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1030 PRINT "PICK UP RECESSED";LS
1040 PRINT "MIN LIFT-OFF=";L6;"LIFT-OFF 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 PROGRAM BEGINS
1110 REM FØR INTEGRATIONS
1120 G0 SUB 1500
1130 REM FØR INDUCTANCES AND CIRCUIT; MAGNITUDE AND PHASE
1140 G0 SUB 6000
1150 REM FØR DISCRIMINATOR VOLTAGE AND PHASE SHIFT
1160 G0 SUB 6500
1170 REM FØR PRINTING ØF RESULTS
1180 G0 SUB 6700
1190 REM FØR AV. PHASE SHIFT AND LIFT-OFF ERROR
1200 G0 SUB 7000
1400 REM FØR COIL AND ATTENUATOR DESIGNS, AND DRIFT
1410 G0 T0 7200
1499 REM SUBROUTINE FØR INTEGRATION
1500 A3=0
1510 A4=0
1520 FOR I=1 TO 3
1530 FOR J=1 TO 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 FOR X=B1+S1/2 TO B2 STEP S1
1670 G0 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 SUBROUTINE FØR L-FACTOR AND INTEGRANTS
1999 REM FØR J-FACTOR
2000 G0 SUB 2700
2010 W5=0
2020 W2=0
2030 W6=0
2040 W7=0
2050 W4=1
2060 W8=1

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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*W3*W4*W5*W8*S3
2250 A6=W6*W6*W3*W3*S4
2260 A7=W6*W6*W4*W4*W5*W5*W8*SS
2270 L(1)=1
2280 FOR J=2 TO 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 FOR GAMMA FACTOR
2330 G0 SUB 3200
2340 FOR I=1 TO 3
2350 FOR J=1 TO 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)*SS
2480 RETURN
2699 REM SUBROUTINE FOR J5=J(R1,R2)/X+3, J6=J(R3,R4)/X+3
2700 R=R1
2710 G0 SUB 2900
2720 J1=Q2
2730 R=R2
2740 G0 SUB 2900
2750 J5=Q2-J1
2760 R=R3
2770 G0 SUB 2900
2780 J3=Q2
2790 R=R4
2800 G0 SUB 2900
2810 J6=Q2-J3
2820 S3=S1*J5*J6

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2830 S4=S1*J5*JS
2840 S5=S1*J6*J6
2850 RETURN
2899 REM SUBROUTINE FOR 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 FOR Q=1 TO Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 GO TO 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*COS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3198 REM SUBROUTINE FOR GAMMA FACTOR(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 FOR GAMMA FACTOR
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=Q5*Q3-Y2*Q1
3460 T7=Q5*Q1-Y2*Q3
3470 T8=Q5*Q3+Y2*Q1
3480 FOR I=1 TO 3
3490 C0=2*C(I)/R5*U2
3500 IF X2*X0>30 THEN 3590
3510 Q7=EXP(X2*C0)
3520 Q8=Q7*COS(Y2*C0)
3530 Q9=Q7*SIN(Y2*C0)
3540 V3=T1+T5*Q8-T6*Q9

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3550 V4=T2+T5*Q9+T6*Q8
3560 V7=T3+T7*Q8-T8*Q9
3570 V8=T4+T7*Q9+T8*Q8
3580 G0 T0 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 SUBROUTINE FOR CIRCUIT, MAGNITUDE, AND PHASE
6000 N1=N3/((R2-R1)*L3)
6010 N2=N4/((R4-R3)*L4)
6020 G0=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 FOR I=1 TO 3
6080 FOR J=1 TO 5
6090 Z8=00*N1*N2*A(I,J)
6100 Z9=00*N1*N2*B(I,J)
6110 Z=00*N1*N1*C(I,J)
6120 Z2=00*N1*N1*(D(I,J)+A3)
6130 Z1=00*N2*N2*E(I,J)
6140 Z3=00*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=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 SUBROUTINE FOR DISC. VOLTAGE AN PHASE SHIFT
6500 Q1=M(2,5)*SIN(P(2,5))-M(2,1)*SIN(P(2,1))
6510 Q2=-M(2,5)*COS(P(2,5))+M(2,1)*COS(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 Q1=Q3
6556 Q2=V1
6560 FOR I=1 TO 3
6570 FOR J=1 TO 5

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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 SUBROUTINE FOR PRINTING RESULTS
6700 PRINT "DRIVER RES", "INDUCTANCE", "N0 TURNS", "SHUNT CAP", "N0R IM PT"
6710 PRINT R6, Q0*N1*N1*A3/W, N3, C6, (D(2,3)+A3)/A3
6720 PRINT "PICKUP RES", "INDUCTANCE", "N0 TURNS", "SHUNT CAP", "N0R IM PT"
6730 PRINT R7, Q0*N2*N2*A4/W, N4, C7, (F(2,3)+A4)/A4
6740 PRINT "DRIVING VOLT", "SERIES RES", "AMP GAIN", "INPUT IMP"
6750 PRINT V0, R0, G5, R9
6760 PRINT "DISCRIMINATOR VOLTAGE IS"; V1
6770 PRINT
6780 PRINT L6, L6+L2, L6+2*L2, L6+3*L2, L6+4*L2
6790 FOR I=1 TO 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 SUBROUTINE FOR AV. PHASE SHIFT AND LIFT-OFF ERROR
7000 Q1=Q(1,1)
7010 Q2=Q(1,1)
7020 FOR J=2 TO 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 Q=Q
7100 PRINT "PHASE SHIFT"; Q; "LIFT-OFF"; Q1-Q2; "IN %"; 100*(Q1-Q2)/Q
7110 PRINT "IN DEGREE"; Q*P8, (Q1-Q2)*P8
7120 RETURN
7199 REM FOR COIL DESIGN, ATTENUATOR, DRIFT, AND EXIT
7200 PRINT "1 COIL DESIGN 2 ATTEM. DESIGN 3 DRIFT CHECK 4 CON CAL"
7210 INPUT NS
7220 PRINT
7230 N NS G0 TO 7300,8200,8600,9900
7299 REM FOR COIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FOR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 G0 SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER"; N3; "TURNS OF #"; G3; "WIRE";
7390 PRINT Q7; "/LAYER"; Q8; "LAYERS"; R6; "0HM"
7399 REM FOR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
7430 W2=R4

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7440 W3=L4
7450 G0 SUB 7510
7460 N4=02
7470 R7=2*09
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIKE";
7490 PRINT Q7;"/LAYER";08;"LAYERS";R7;"OHMS TOTAL"
7500 G0 T0 1140
7509 REM SUBROUTINE FOR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FOR 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*(LOG(Q6)-LOG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 G0 T0 7590
7630 G=INT(G)
7639 REM FOR 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*LOG(Q5*1E3)-.43444)*1E-3+Q5
7680 G0 T0 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 FOR ATTENUATOR 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=01
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));"BELOW RES";
8330 PRINT SQR(Q1/C6);"OPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELOW RES";
8350 PRINT SQR(Q2/C7);"OPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 G0 T0 1140
8599 REM FOR DRIFTS
8600 PRINT"SYSTEM DRIFT VARIATIONS"
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","% OF RANGE"
8720 IF E1=0 THEN 8770
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 G0 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 G0 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 G0 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 G0 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 G0 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 G0 SUB 9320
9010 R9=R9/(1+E8)
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VOLT",
9050 G0 SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 G0 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 G0 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 G0 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 G0 SUB 9300
9260 K2=K2/(1+A9)
9270 G0 T0 7200
9299 REM SUBROUTINE FOR DRIFT
9300 G0 SUB 600
9310 G0 SUB 1500
9320 G0 SUB 6000
9330 Q1=0
9340 FOR I=1 TO3
9350 FOR J=1 TO 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*Q1/0
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:

<u>Line Number</u>	<u>Constant</u>	<u>Parameter Varied</u>
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.

```
00250      R5 = .08325
00260      R1 = .75
00270      R2 = 1.25
00280      L3 = .36
00290      R3 = .36
00300      R4 = .696
00310      L4 = .096
00320      L5 = 0.0
00330      L6 = .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.
00430      GAIN = 1
00440      FREQ = 1.0E4
00450      L2 = .025
00460      RH01 = 5.39261
00470      U1 = 1.
00480      RH02 = 3.63204
00490      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.

```

00010C IN THIS PROGRAM, THE BASE RESISTIVITY IS RH01 AND
00020C   THE CLADDING RESISTIVITY IS RH02
00030C SIGMA IS THE GAMMA FACTOR
00040      COMPLEX BETA1,BETA2,EX1,RNUM,DEN,SIGMA
00050      COMPLEX TMUT,DRIVER,PICKUP
00060      REAL L3,L4,L5,L6,L2,N3,N4,K1,K2
00070      COMMON X,Z,Q1,PI/B1/R1,R2,R3,R4,L3,L4,R0,R6,R7
00080      COMMON /B1/R9,C6,C7,V0,GAIN,W,FREQ,R5,N3,N4
00090      COMMON /B2/TMUT,DRIVER,PICKUP,AIR1,AIR2/B3/GAGE,XIN
00100      COMMON /B3/XOUT,XLEN,TURNs,N1A,J1,PERLAY,XEAY
00110      DIMENSION CLAD(3),RL(5),SIGMA(3),TMUT(3,5),DRIVER(3,5)
00120      DIMENSION PICKUP(3,5),TMAG(3,5),PHASE(3,5),SHIFT(3,5)
00130      EQUIVALENCE (RH01,K1),(RH02,K2),(GAIN,G5),(FREQ,F)
00140      PI=3.14159265
00150      RAD=180.0/PI
00160C
00170C
00180C
00190C
00200C
00210C
00220      JKL=0
00230C THE FOLLOWING ARE INPUT DATA FOR THE PARAMETERS OF
00240C   THE COILS, MATERIAL, AND CIRCUIT
00250      R5=.08325
00260      R1=.75
00270      R2=1.25
00280      L3=.36
00290      R3=.36
00300      R4=.696
00310      L4=.096
00320      L5=0.0
00330      L6=.1
00340      R6=79.36
00350      R7=530.5
00360      N3=360.0
00370      N4=410.0
00380      R0=1.0E6
00390      R9=1.0E6
00400      C6=1.0E-12
00410      C7=1.0E-12
00420      V0=10.0
00430      GAIN=1.0
00440      FREQ=1.0E4
00450      L2=0.025
00460      RH01=5.393
00470      U1=1.0
00480      RH02=3.632
00490      U2=1.0
00500      CLAD(1)=0.0266
00510      CLAD(2)=0.028
00520      CLAD(3)=0.0294
00530      5 W=2.0*PI*FREQ
00540      IF(RH01.GT.1.0E9) G0 T0 10
00550      RM1=0.5094*U1*FREQ*R5*R5/RH01
00560      G0 T0 20
00570      10 RM1=0.0

```

```

00580   20 RM2=0.5094*U2*FREQ*R5*R5/RH02
00590C THE SYSTEM PARAMETERS ARE PRINTED OUT
00600   IF(JKL.NE.0) G0 T0 105
00610   TYPE 30,R1,R2,L3
00620   30 F0RFORMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
00630   1F8.5)
00640   TYPE 40,R3,R4,L4
00650   40 F0RFORMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
00660   1F8.5)
00670   TYPE 50,R5,FREQ
00680   50 F0RFORMAT(1H ,17HC0IL MEAN RADIUS=,F8.5,7H INCHES,3X,
00690   120H0PERATING FREQUENCY=,1PE12.5)
00700   TYPE 60,L5
00710   60 F0RFORMAT(1H ,15HPICKUP RECESSED,F8.5)
00720   TYPE 70,L6,L2
00730   70 F0RFORMAT(1H ,13HMIN LIFT-OFF=,F8.5,3X,19HLIFT-OFF INCREMENT=,
00740   1F8.5)
00750   TYPE 80,UI,RM1,RH01
00760   80 F0RFORMAT(1H ,3HU1=,F6.2,5X,3HM1=,F9.5,2X,12HRESISTIVITY=,
00770   11PE12.5,11H MICR0HM CM)
00780   TYPE 90,U2,RM2,RH02
00790   90 F0RFORMAT(1H ,3HU2=,F6.2,5X,3HM2=,F9.5,2X,12HRESISTIVITY=,
00800   11PE12.5,11H MICR0HM CM)
00810   TYPE 100,CLAD(1),CLAD(2),CLAD(3)
00820   100 F0RFORMAT(1H ,10HTHICKNESS=,F8.5,2(8X,F8.5))
00830C THE INTEGRATION IS PERFORMED BY THE TRAPEZOIDAL METHOD,
00840C EVALUATING AT THE CENTER OF THE INTERVAL; FOR X LARGE
00850C THE INTEGRAL CONVERGES RAPIDLY. SO LARGER INTERVALS
00860C ARE TAKEN
00870C IN THE INTEGRATION TMUT, DRIVER, PICKUP, AIR1, AND
00880C AIR2 ARE CALCULATED
00890   105 S1=0.01
00900   S2=5.0
00910   B1=0.0
00920   B2=S2
00930   AIR1=0.0
00940   AIR2=0.0
00950   D0 108 J=1,3
00960   D0 108 K=1,5
00970   DRIVER(J,K)=(0.0,0.0)
00980   PICKUP(J,K)=(0.0,0.0)
00990   TMUT(J,K)=(0.0,0.0)
01000   108 CONTINUE
01010   110 I1=(B2-B1)/S1
01020   X=B1-S1/2.0
01030   D0 170 I=1,I1
01040   X=X+S1
01050   Z=R2*X
01060   Q1=R2
01070C SUBROUTINE BESEL EVALUATES THE INTEGRAL OF
01080C THE PRODUCT OF THE BESEL FUNCTION AND ITS
01090C ARGUMENT
01100   CALL BESEL(VAL2)
01110   Z=R1*X
01120   Q1=R1
01130   CALL BESEL(VAL1)

```

```

01140      Z=R4*X
01150      Q1=R4
01160      CALL BESEL(VAL4)
01170      Z=R3*X
01180      Q1=R3
01190      CALL BESEL(VAL3)
01200      S3=S1*(VAL4-VAL3)*(VAL2-VAL1)
01210      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
01220      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
01230      EX3=EXP(-X*L3)
01240      W1=1.0-EX3
01250      EX4=EXP(-X*L4)
01260      W2=1.0-EX4
01270      EX5=EXP(-X*L5)
01280      W3=EX3/(EX4*EX4*EX5*EX5)
01290      IF(X.GT.30.0) G0 T0 160
01300C FR0M HERE THROUH LINE 130,SIGMA IS CALCULATED
01310      BETA2=CSQRT(CMPLX(X*X,RM2))/U2
01320      D0 130 J=1,3
01330      IF(REAL(CLAD(J)/R5*BETA2*U2).GT.15.0) G0 T0 120
01340      EX1=CEXP(2.0*CLAD(J)/R5*BETA2*U2)
01350      BETA1=CSQRT(CMPLX(X*X,RM1))/U1
01360      RNUM=(X+BETA2)*(BETA2-BETA1)+(X-BETA2)*(BETA2+BETA1)*EX1
01370      DEN=(X-BETA2)*(BETA2-BETA1)+(X+BETA2)*(BETA2+BETA1)*EX1
01380      SIGMA(J)=RNUM/DEN
01390      G0 T0 130
01400      120 SIGMA(J)=(X-BETA2)/(X+BETA2)
01410      130 C0NTINUE
01420      EX2=EXP(-2.0*X*L2)
01430      EX6=EXP(-2.0*X*L6)
01440      W4=1.0-EX4*W3
01450      W5=EX5*EX6*W1*W2*W4
01460      W6=EX6*W1*W1
01470      W7=W2*W2*EX6*EX5*EX5*W4*W4
01480      RL(1)=1.0
01490      D0 140 K=2,5
01500      140 RL(K)=EX2*RL(K-1)
01510      D0 150 K=1,3
01520      D0 150 L=1,5
01530      TMUT(K,L)=TMUT(K,L)+S3*W5*RL(L)*SIGMA(K)
01540      DRIVER(K,L)=DRIVER(K,L)+S4*W6*RL(L)*SIGMA(K)
01550      150 PICKUP(K,L)=PICKUP(K,L)+S5*W7*RL(L)*SIGMA(K)
01560      160 AIR1=AIR1+S4*2.0*(X*L3-W1)
01570      AIR2=AIR2+S5*(4.0*(X*L4-W2)-2.0*W2*W2*W3)
01580      170 C0NTINUE
01590      B1=B2
01600      B2=B2+S2
01610      S1=0.05
01620      IF(X.LT.9.0) G0 T0 110
01630      S1=0.1
01640      IF(X.LT.29.0) G0 T0 110
01650      S1=0.2
01660      IF(X.LT.39.0) G0 T0 110
01670      S1=0.5
01680      IF(X.LT.79.0) G0 T0 110
01690C THE INTEGRATION ENDS HERE
01700      IF(JKL.NE.0) G0 T0 552
01710C NEXT THE PROPERTIES OF THE COILS ARE DETERMINED AND PRINTED

```

```

01720 180 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
01730      CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
01740      TYPE 190
01750 190 FORMAT(1H ,10H DRIVER RES,4X,10H INDUCTANCE,4X,8HN0 TURNS,
01760      16X,9H SHUNT CAP,5X,9HN0R IM PT)
01770      Q1=Q0*T1*T1*AIR1/W
01780      Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
01790      Q3=Q0*T2*T2*AIR2/W
01800      Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
01810      TYPE 200,R6,Q1,N3,C6,Q2
01820 200 FORMAT(1H ,1PE12.5,2X,1PE12.5,2X,0PF8.1,6X,1PE12.5,2X,
01830      10PF9.6)
01840      TYPE 210
01850 210 FORMAT(1H ,10H PICKUP RES,4X,10H INDUCTANCE,4X,8HN0 TURNS,
01860      16X,9H SHUNT CAP,5X,9HN0R IM PT)
01870      TYPE 200,R7,Q3,N4,C7,Q4
01880      TYPE 220
01890 220 FORMAT(1H ,12H DRIVING VOLT,2X,10H SERIES RES,4X,
01900      18H AMP GAIN,6X,9H INPUT IMP)
01910      TYPE 230,V0,R0,GAIN,R9
01920 230 FORMAT(1H ,F5.1,9X,1PE12.5,2X,0PF8.1,6X,1PE12.5)
01930      TYPE 240,V1
01940 240 FORMAT(1H ,22H DISCRIMINATOR VOLTAGE=,1PE12.5)
01950      TYPE 250
01960 250 FORMAT(1H )
01970      RL(1)=L6
01980      D0 260 I=2,S
01990 260 RL(I)=L2+RL(I-1)
02000      TYPE 270,RL
02010 270 FORMAT(1H ,4(F6.3,8X),F6.3)
02020      TYPE 250
02030C THE VOLTAGE MAGNITUDE, PHASE, AND SHIFT ARE PRINTED FOR
02040C THE VARIOUS LIFT-OFF VALUES
02050      D0 280 I=1,3
02060      TYPE 290,(TMAG(I,J),J=1,5)
02070      TYPE 290,(PHASE(I,J),J=1,5)
02080      TYPE 290,(SHIFT(I,J),J=1,5)
02090      TYPE 250
02100 280 CONTINUE
02110 290 FORMAT(1H ,4(1PE12.5,2X),1PE12.5)
02120      CALL SENS(SHIFT,RAD,SEN)
02130C THE USER SELECTS ONE OF FOUR POSSIBILITIES
02140 295 TYPE 300
02150 300 FORMAT(' 1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK
02160      1 4 CON CAL')
02170      TYPE 250
02180      ACCEPT 310,NS
02190 310 FORMAT(1I)
02200      G0 T0(320,450,540,690),NS
02210C THE FIRST POSSIBILITY PRINTS FACTORS IN THE COIL
02220C DESIGN; USER INPUTS INTEGER DATA AS REQUESTED
02230 320 TYPE 330
02240 330 FORMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
02250      1 TURNS')
02260      TYPE 250
02270      ACCEPT 340,N1A,N2A,N3A,N4A
02280 340 FORMAT(4I)
02290      IF (N1A*N2A.EQ.0) G0 T0 350

```

```

02300      GAGE=N1A
02310      XIN=R1*R5
02320      X0UT=R2*R5
02330      XLEN=L3*R5
02340      TURNS=N2A
02350      N3=N2A
02360      N1A=-1
02370      J1=1
02380      CALL GAGER(R6)
02390      G0 T0 370
02400 350 IF(N1A.EQ.0) G0 T0 360
02410      GAGE=N1A
02420      XIN=R1*R5
02430      X0UT=R2*R5
02440      XLEN=L3*R5
02450      J1=1
02460      CALL GAGER(R6)
02470      N3=TURES
02480      G0 T0 370
02490 360 IF(N2A.EQ.0) G0 T0 390
02500      N3=N2A
02510      TURNS=N2A
02520      XIN=R1*R5
02530      X0UT=R2*R5
02540      XLEN=L3*R5
02550      J1=0
02560      CALL GAGER(R6)
02570 370 TYPE 380,TURNS,GAGE,PERLAY,XLAY,R6
02580 380 FORMAT(1H ,6H DRIVER,F6.1,10H TURNS 0F#,F5.1,4HWIRE,
02590 1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
02600 390 IF(N3A*N4A.EQ.0) G0 T0 400
02610      GAGE=N3A
02620      TURNS=N4A
02630      N4=N4A
02640      XIN=R3*R5
02650      X0UT=R4*R5
02660      XLEN=L4*R5
02670      J1=1
02680      CALL GAGER(R7)
02690      R7=2.0*R7
02700      G0 T0 420
02710 400 IF(N3A.EQ.0) G0 T0 410
02720      GAGE=N3A
02730      XIN=R3*R5
02740      X0UT=R4*R5
02750      XLEN=L4*R5
02760      J1=1
02770      CALL GAGER(R7)
02780      N4=TURES
02790      R7=2.0*R7
02800      G0 T0 420
02810 410 IF(N4A.EQ.0) G0 T0 440
02820      N4=N4A
02830      TURNS=N4A
02840      XIN=R3*R5
02850      X0UT=R4*R5
02860      XLEN=L4*R5
02870      J1=0

```

```

02880    CALL GAGER(R7)
02890    R7=2.0*R7
02900    420 TYPE 430,TURNS,GAGE,PERLAY,XLAY,R7
02910    430 FORMAT(1H ,6HPICKUP,F6.1,10H TURNS EA#,F5.1,4HWIRE,
02920      1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
02930    440 GO TO 180
02940C THE SECOND POSSIBILITY DEALS WITH ATTENUATOR DESIGNS;
02950C   USER INPUTS REQUESTED DATA IN E FIELD TYPE
02960    450 TYPE 460
02970    460 FORMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
02980      1 SHUNT CAP')
02990    TYPE 250
03000    ACCEPT 470,P1,P2,P3,P4
03010    470 FORMAT(4E)
03020      IF(P1.EQ.0.0) GO TO 480
03030      R0=P1
03040    480 IF(P2.EQ.0.0) GO TO 490
03050      C6=P2
03060    490 IF(P3.EQ.0.0) GO TO 500
03070      R9=P3
03080    500 IF(P4.EQ.0.0) GO TO 510
03090      C7=P4
03100    510 Q5=1.0/(W*SQRT(Q1*Q2*C6))
03110    Q6=SQRT(Q1*Q2/C6)
03120    Q7=R0/(W*Q1*Q2)
03130    Q8=1.0/(W*SQRT(Q3*Q4*C7))
03140    Q9=SQRT(Q3*Q4/C7)
03150    Q10=R9/(W*Q3*Q4)
03160    TYPE 520,Q5,Q6,Q7
03170    520 FORMAT(1H ,7HDVR CKT,1PE12.5,10H BELOW RES,1PE12.5,
03180      18H OPT RES,1PE12.5,11H RES/REACT.)
03190    TYPE 530,Q8,Q9,Q10
03200    530 FORMAT(1H ,7HP-U CKT,1PE12.5,10H BELOW RES,1PE12.5,
03210      18H OPT RES,1PE12.5,11H RES/REACT.)
03220    GO TO 180
03230C THE THIRD POSSIBILITY EXAMINES THE EFFECTS OF DRIFT
03240C ON THE SYSTEM
03250    540 TYPE 550
03260    550 FORMAT(1H ,23HSYSTEM DRIFT VARIATIONS)
03270    DR1=0.01
03280    DR2=0.01
03290    DR3=0.01
03300    DR4=0.01
03310    DR5=0.01
03320    DR6=0.01
03330    DR7=0.01
03340    DR8=0.01
03350    DR9=0.01
03360    DR10=0.01
03370    DR11=0.01
03380    GO TO 559
03390    552 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03400    GO TO (675,678,681,684),JKL
03410    559 TYPE 560
03420    560 FORMAT(1H ,11HZ VARIATION,3X,13HPARAMETER VAR,1X,
03430      17HRADIANS,7X,7HDEGREES,7X,10HZ OF RANGE)
03440      IF(DR1.EQ.0.0) GO TO 580

```

```

03450      R6=R6*(1.0+DR1)
03460      DR100=100.0*DR1
03470      TYPE 570,DR100
03480 570 FORMAT(1H ,F4.1,10X,13H DRIVER RES    $)
03490      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03500      R6=R6/(1.0+DR1)
03510 580 IF(DR2.EQ.0.0) G0 T0 600
03520      R7=R7*(1.0+DR2)
03530      DR100=100.0*DR2
03540      TYPE 590,DR100
03550 590 FORMAT(1H ,F4.1,10X,13H PICKUP RES    $)
03560      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03570      R7=R7/(1.0+DR2)
03580 600 IF(DR3.EQ.0.0) G0 T0 620
03590      C6=C6*(1.0+DR3)
03600      DR100=100.0*DR3
03610      TYPE 610,DR100
03620 610 FORMAT(1H ,F4.1,10X,13H DVR SHUNT CAP$)
03630      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03640      C6=C6/(1.0+DR3)
03650 620 IF(DR4.EQ.0.0) G0 T0 640
03660      C7=C7*(1.0+DR4)
03670      DR100=100.0*DR4
03680      TYPE 630,DR100
03690 630 FORMAT(1H ,F4.1,10X,13H P-U SHUNT CAP$)
03700      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03710      C7=C7/(1.0+DR4)
03720 640 IF(DR5.EQ.0.0) G0 T0 660
03730      R0=R0*(1.0+DR5)
03740      DR100=100.0*DR5
03750      TYPE 650,DR100
03760 650 FORMAT(1H ,F4.1,10X,13H SERIES RES    $)
03770      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03780      R0=R0/(1.0+DR5)
03790 660 IF(DR6.EQ.0.0) G0 T0 671
03800      R9=R9*(1.0+DR6)
03810      DR100=100.0*DR6
03820      TYPE 670,DR100
03830 670 FORMAT(1H ,F4.1,10X,13H AMP INPUT RES$)
03840      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03850      R9=R9/(1.0+DR6)
03860 671 IF(DR7.EQ.0.0) G0 T0 673
03870      V0=V0*(1.0+DR7)
03880      DR100=100.0*DR7
03890      TYPE 672,DR100
03900 672 FORMAT(1H ,F4.1,10X,13H APPLIED VOLT.$)
03910      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
03920      V0=V0/(1.0+DR7)
03930 673 IF(DR8.EQ.0.0) G0 T0 676
03940      FREQ=FREQ*(1.0+DR8)
03950      DR100=100.0*DR8
03960      TYPE 674,DR100
03970 674 FORMAT(1H ,F4.1,10X,13H FREQUENCY     $)
03980      JKL=1
03990      G0 T0 5
04000 675 FREQ=FREQ/(1.0+DR8)
04010      JKL=0
04020 676 IF(DR9.EQ.0.0) G0 T0 679

```

```

04030      R5=R5*(1.0+DR9)
04040      DR100=100.0*DR9
04050      TYPE 677,DR100
04060      677 F0RMA7(1H ,F4.1,10X,13HMEAN RADIUS $)
04070      JKL=2
04080      G0 T0 5
04090      678 R5=R5/(1.0+DR9)
04100      JKL=0
04110      679 IF(DR10.E0.0.0) G0 T0 682
04120      RH01=RH01*(1.0+DR10)
04130      DR100=100.0*DR10
04140      TYPE 680,DR100
04150      680 F0RMA7(1H ,F4.1,10X,13HBASE RESISTVY$)
04160      JKL=3
04170      G0 T0 5
04180      681 RH01=RH01/(1.0+DR10)
04190      JKL=0
04200      682 IF(DR11.E0.0.0) G0 T0 295
04210      RH02=RH02*(1.0+DR11)
04220      DR100=100.0*DR11
04230      TYPE 683,DR100
04240      683 F0RMA7(1H ,F4.1,10X,13HCLADDING RES $)
04250      JKL=4
04260      G0 T0 5
04270      684 RH02=RH02/(1.0+DR11)
04280      JKL=0
04290      G0 T0 295
04300C THE FOURTH POSSIBILITY ENDS CALCULATIONS
04310      690 CALL EXIT
04320      END
04330      SUBROUTINE BESEL(VAL)
04340      COMMON X,Z,Q1,PI
04350      IF(Z.GT.5.0) G0 T0 1010
04360      K=2.0*Z
04370      L=K+3
04380      F1=0.5*Q1*Q1*Q1
04390      VAL=F1/3.0
04400      D0 1000 I=1,L
04410      AI=I
04420      F1=-F1*0.25*Z*Z/(AI*AI+AI)
04430      VAL=VAL+F1/(2.0*AI+3.0)
04440      1000 C0NTINUE
04450      G0 T0 1020
04460      1010 X0=(((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
04470      X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
04480      X1=(((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
04490      X1=(X1-0.187344E-2)/Z+0.7979095
04500      VAL=(1.0-SQRT(Z)*(X1*COS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
04510      1(X*X*X)
04520      1020 RETURN
04530      END
04540      SUBROUTINE PHASET(A,B,C,V1,03)
04550      DIMENSION A(3,5),B(3,5),C(3,5)
04560      01=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
04570      02=-(A(2,5)*COS(B(2,5))-A(2,1)*COS(B(2,1)))
04580      03=ATAN2(01,02)
04590      V1=A(2,1)*SIN(03+B(2,1))
04600      D0 2000 I=1,3

```

```

04610      D0 2000 J=1,5
04620 2000 C(I,J)=03-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(I,J)
04630      RETURN
04640      END
04650      SUBROUTINE SENS(0,RAD,01)
04660      DIMENSION 0(3,5)
04670      09=0(1,1)
04680      00=0(1,1)
04690      D0 3010 I=2,5
04700      IF(0(1,1).LT.09) G0 T0 3000
04710      09=0(1,I)
04720 3000 IF(0(1,1).GT.00) G0 T0 3010
04730      00=0(1,I)
04740 3010 C0NTINUE
04750      01=(0(1,1)+0(1,2)+0(1,3)+0(1,4)+0(1,5))/5.0
04760      01=01-(0(3,1)+0(3,2)+0(3,3)+0(3,4)+0(3,5))/5.0
04770      XL0=09-00
04780      PERCT=100*XL0/01
04790      DEGR1=01*RAD
04800      DEGR2=XL0*RAD
04810      TYPE 3020,01,XL0,PERCT
04820 3020 F0RMLAT(1H ,12PHASE SHIFT=,1PE12.5,2X,8HLIFT0FF=,
04830           11PE12.5,2X,2H%,,1PE12.5)
04840      TYPE 3030,DEGR1,DEGR2
04850 3030 F0RMLAT(1H ,7HDEGREE:,1PE13.5,5X,1PE13.5)
04860      RETURN
04870      END
04880      SUBROUTINE GAGER(RES)
04890      COMMON /B3/G,D1,D2,RLN,T5,N1,J1,D,E
04900      PI=3.1415926536
04910      IF(J1.EQ.1) G0 T0 4015
04920      N1=-1
04930      D3=0.95*SQRT((D2-D1)*RLN/T5)
04940      X2=1.0371E-5/(D3*D3)
04950      Q=40.0
04960 4000 G=40.0+10.0*(ALOG(X2)-ALOG(.9989+.017*(Q/10.0-1.0)))/2.3
04970      10259
04980      IF(ABS(Q-G).LT.1.0E-4) G0 T0 4010
04990      Q=G
05000      G0 T0 4000
05010 4010 IG=G
05020      G=IG
05030 4015 X2=(.9989+.017*(G/10.0-1.0))*10.0**((G/10.0-4.0)
05040      D3=SQRT(1.0371E-5/X2)
05050      IF(G.GT.40.0) G0 T0 4020
05060      X3=(-.460655*ALOG(D3*1.E3)-.43444)*1.E-3
05070      G0 T0 4030
05080 4020 X3=(-.02228*D3+2.56791E-2)*1.E-3
05090 4030 ID=(RLN/(D3+X3))
05100      D=ID
05110      IE=(D2-D1)/(D3+X3)
05120      E=IE
05130      IF(N1.EQ.-1) G0 T0 4040
05140      T5=D*E
05150 4040 RES=T5*X2*(D2+D1)*PI/12.0
05160      RETURN
05170      END

```

```

05180      SUBROUTINE CIRCT(TMAG,PHASE,Q0,T1,T2)
05190      COMMON /B1/R1,R2,R3,R4,RL3,RL4,R0,R6,R7,R9,C6,C7,V0,GAIN
05200      COMMON /B1/W,FREQ,RBAR,TURN1,TURN2/B2/TMUT,DRIVER
05210      COMMON /B2/PICKUP,AIR1,AIR2
05220      COMPLEX TMUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
05230      COMPLEX DENOM,TNUM,VOLT
05240      DIMENSION TMUT(3,5),DRIVER(3,5),PICKUP(3,5)
05250      DIMENSION TMAG(3,5),PHASE(3,5)
05260      T1=TURN1/((R2-R1)*RL3)
05270      T2=TURN2/((R4-R3)*RL4)
05280      Q0=6.300475204E-7*FREQ*RBAR
05290      Z1=CMPLX(W*R0*C6,-1.0)
05300      Z2=CMPLX(W*R9*C7,-1.0)
05310      Z3=CMPLX(0.0,-R0)
05320      Z4=CMPLX(0.0,-R9)
05330      D0 5000 I=1,3
05340      D0 5000 J=1,5
05350      Z5=Q0*T1*T2*TMUT(I,J)
05360      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(I,J)+AIR1)
05370      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
05380      DENOM=Z1*Z2*Z5*Z6+(Z1*(Z6+R6)+Z3)*
05390      5 (Z2*(Z7+R7)+Z4)
05400      TNUM=V0*R9*GAIN*(0.0,-1.0)*Z5
05410      VOLT=TNUM/DENOM
05420      TMAG(I,J)=CABS(VOLT)
05430 5000 PHASE(I,J)=ATAN2(AIMAG(VOLT),REAL(VOLT))
05440      RETURN
05450      END
05460      SUBROUTINE CIRCT1(01,V1,0,RAD,SEN)
05470      DIMENSION 0(3,5),TMAG(3,5),PHASE(3,5)
05480      CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
05490      Q1=0.0
05500      D0 6000 I=1,3
05510      D0 6000 J=1,5
05520      Q2=01-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
05530      1+PHASE(I,J)-0(I,J)
05540      IF(ABS(Q1).GT.ABS(Q2)) G0 T0 6000
05550      Q1=Q2
05560 6000 CONTINUE
05570      Q2NEW=RAD*Q1
05580      Q3=100.0*Q1/SEN
05590      TYPE 6010,01,Q2NEW,Q3
05600 6010 F0RFORMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
05610      RETURN
05620      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      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 conductivity
          variation, refer to Fig. 4)
670      M0 = (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  $N$ th layer conductor  
in inches,

$K(N)$  = numerical value of resistivity of the  $N$ th layer con-  
ductor in microhm centimeters,

$U(N)$  = numerical value of relative permeability of the  $N$ th  
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	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\*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  $R_s^2 \omega \mu_N \sigma_N$  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,  $R_0$ , the driver shunt capacitance,  $C_6$ , the amplifier input impedance,  $R_9$ , and the shunt capacitance in the pickup circuit,  $C_7$ , 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:

<u>Parameter</u>	<u>Line Number</u>	<u>Constant</u>
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  $3.632 \mu\Omega\text{-cm}$ . Below the surface cladding, the next conductor is  $19\frac{1}{4}$  mils thick and has a resistivity of  $5.393 \mu\Omega\text{-cm}$ . Finally, there is another layer of cladding material, with a thickness of 28 mils and resistivity of  $3.632 \mu\Omega\text{-cm}$ . The driver coil has a mean radius of 0.08325 in., inner and outer radii of 0.0625 and  $0.10\frac{1}{4}$  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  $79.36 \Omega$ , and the pickup coils have 410 turns each of No.  $5\frac{1}{4}$  wire, with a resistance of  $530.5 \Omega$  for both coils. The driver series and the pickup amplifier input resistances are both chosen to be  $1 M\Omega$ . The shunt capacitances in both circuits are chosen to be  $1 \text{ pF}$ . 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  $\pm 5\%$ . 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-0HM 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 VARIATION OF 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  
 COIL MEAN RADIUS 8.32500E-2 INCHES      OPERATING FREQUENCY 10000  
 PICK UP RECESSED 0  
 MIN LIFT-OFF= 0.1 LIFT-OFF INCREMENT= 0.025  
 DRIVER RES      INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT  
 79.36      6.05067E-4      360      1.00000E-12      0.849616  
 PICKUP RES      INDUCTANCE      NO TURNS      SHUNT CAP      NOR IM PT  
 530.5      4.72124E-4      410      1.00000E-12      0.992308  
 DRIVING VOLT      SERIES RES      AMP GAIN      INPUT IMP  
 10      1000000      1      1000000  
 DISCRIMINATOR VOLTAGE 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-OFF 2.32629E-4 IN % 3.44449					
IN DEGREE 0.386957      1.33287E-2					
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL					
?1					

## DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS

?46,0,54,0

DRIVER 391	TURNS OF # 46 WIRE 17 /LAYER 23 LAYERS	71.9293 0HM		
PICKUP 429	TURNS EA # 54 WIRE 11 /LAYER 39 LAYERS	532.582 OHMS TOTAL		
DRIVER RES	INDUCTANCE	N0 TURNS	SHUNT CAP	N0R IM PT
71.9293	7.13760E-4	391	1.00000E-12	0.849616
PICKUP RES	INDUCTANCE	N0 TURNS	SHUNT CAP	N0R IM PT
532.582	5.16896E-4	429	1.00000E-12	0.992308
DRIVING VOLT	SERIES RES	AMP GAIN	INPUT IMP	
10	1000000	1	1000000	
DISCRIMINATOR VOLTAGE 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-OFF 2.32629E-4 IN % 3.44449				
IN DEGREE 0.386957 1.33287E-2				
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?2</u>				

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 BELOW RES 359.202 OPT RES 13.1225 RES/REACTANCE  
P-U CT 10.2505 BELOW RES 330.351 OPT 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 VOLT SERIES RES AMP GAIN INPUT IMP  
10 500 1 620  
DISCRIMINATOR VOLTAGE 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-OFF 1.31831E-4 IN % 1.96603				
IN DEGREE 0.384192 7.55334E-3				
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				

?3

SYSTEM DRIFT VARIATIONS				
% VARIATN	PARAMETER	RADIAN	DEGREE	% OF 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 VOLT	-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 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON 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 MULTICK(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-0HM CM)","M,SIGMA","U"
535 FOR N=1 TO N9
537 READ T(N),R(N),U(N)
539 NEXT N
540 G0 SUB 600
550 FOR N=1 TO N9
560 PRINT N,T(N),R(N),S(N),U(N)
570 NEXT N
580 G0 T0 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*K5*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 "CONDUCTIVITY VARIATION OF";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 COIL DATA
1000 PRINT "R1=";R1,"R2=";R2,"DRIVER LENGTH IS";L3
1010 PRINT "R3=";R3,"R4=";R4,"PICK UP LENGTH IS";L4
1020 PRINT "COIL MEAN RADIUS";R5;"INCHES      OPERATING FREQUENCY";F
1030 PRINT "PICK UP RECESSED";L5
1040 PRINT "MIN LIFT-OFF=";L6;"LIFT-OFF INCREMENT=";L2
1100 REM PROGRAM BEGINS
1110 REM FOR INTEGRATIONS
1120 G0 SUB 1500
1130 REM FOR INDUCTANCES AND CIRCUIT; MAGNITUDE AND PHASE
1140 G0 SUB 6000
1150 REM FOR DISCRIMINATOR VOLTAGE AND PHASE SHIFT
1160 G0 SUB 6500
1170 REM FOR PRINTING OF RESULTS
1180 G0 SUB 6700
1190 REM FOR AV. PHASE SHIFT AND LIFT-OFF ERROR
1200 G0 SUB 7000
1400 REM FOR COIL AND ATTENUATOR DESIGNS, AND DRIFT
1410 G0 T0 7200
1499 REM SUBROUTINE FOR INTEGRATION
1500 A3=0
1510 A4=0
1520 FOR I=1 TO 3
1530 FOR J=1 TO 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 FOR X=B1+S1/2 TO B2 STEP S1
1670 G0 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 SUBROUTINE FOR L-FACTOR AND INTEGRANTS
1999 REM FOR J-FACTOR
2000 G0 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*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 FOR J=2 TO 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 FOR GAMMA FACTOR
2330 G0 SUB 3200
2340 FOR I=1 TO 3
2350 FOR J=1 TO 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 SUBROUTINE FOR JS=J(R1,R2)/X+3, J6=J(R3,R4)/X+3
2700 R=R1

```

```

2710 G0 SUB 2900
2720 J1=02
2730 R=R2
2740 G0 SUB 2900
2750 JS=02-J1
2760 R=R3
2770 G0 SUB 2900
2780 J3=02
2790 R=R4
2800 G0 SUB 2900
2810 J6=02-J3
2820 S3=S1*JS*J6
2830 S4=S1*JS*JS
2840 S5=S1*J6*J6
2850 RETURN
2899 REM SUBROUTINE FOR 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 FOR Q=1 TO Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 G0 T0 3050
3000 Q1=(CC(-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=(CC(-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*COS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3198 REM SUBROUTINE FOR GAMMA FACTOR(K(I),N(I))
3199 REM FOR 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 G0 SUB 5000
3270 X(N)=X1
3280 Y(N)=Y1
3290 Q=Q+X1*T(N)/RS
3300 IF Q>20 THEN 3340
3310 IF N=1 THEN 3340
3320 N=N-1
3330 G0 T0 3240
3340 N7=N
3350 REM FOR CONDUCTIVITY VARIATION
3360 FOR I=1 TO 3
3370 M1=M(I,0)
3380 U1=U(N8)
3390 G0 SUB 5000
3400 X(I,0)=X1
3410 Y(I,0)=Y1
3420 NEXT I
3430 REM FOR GAMMA FACTOR

```

```

3440 IF N8=N7 THEN 3690
3450 IF N8=N7+1 THEN 3690
3460 N=N7+1
3470 G0 SUB 5100
3480 G0 SUB 5150
3490 N6=N8-1
3500 IF N8=N7+2 THEN 3650
3510 IF N8>N7 THEN 3540
3520 N6=N9
3530 IF N7=N9-1 THEN 3980
3540 X0=X(2)
3550 Y0=Y(2)
3560 FOR N=N7+2 TO N6
3570 X1=X(N)
3580 Y1=Y(N)
3590 G0 SUB 5300
3600 G0 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 FOR V(K,M+1) L,I
3710 N=N8+2
3720 G0 SUB 5100
3730 G0 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 FOR N=N8+3 TO N9
3860 X1=X(N)
3870 Y1=Y(N)
3880 G0 SUB 5300
3890 G0 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 FOR I=1 TO 3
3990 IF N8<N7 THEN 4380
4000 IF N8=N7 THEN 4160
4010 X0=X(N8-1)

```

```

4020 Y0=Y(N8-1)
4030 N=N8
4040 X1=X(I,0)
4050 Y1=Y(I,0)
4060 IF N8=N7+1 THEN 4140
4070 G0 SUB 5300
4080 V3=I1
4090 V4=I2
4100 V7=I3
4110 VR=I4
4120 G0 SUB 5580
4130 G0 T0 4160
4140 G0 SUB 5150
4150 REM T(M+1,M>I,P (1(M,M-1)V(M-1,1))P,2
4160 X0=X(I,0)
4170 Y0=Y(I,0)
4180 N=N8+1
4190 X1=X(N)
4200 Y1=Y(N)
4210 IF N8=N7 THEN 4250
4220 G0 SUB 5300
4230 G0 SUB 5580
4240 G0 T0 4260
4250 G0 SUB 5150
4260 IF N8=N9-1 THEN 4380
4270 REM FOR V(K,M+1)L,I .....
4280 T1=V1
4290 T2=V2
4300 T3=15
4310 T4=I6
4320 T5=V5
4330 T6=V6
4340 T7=I7
4350 T8=I8
4360 G0 SUB 5580
4370 REM FOR GAMMA FACTOR
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 SUBROUTINE FOR BETAX1,Y1)
5000 IF M1<01*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 G0 T0 5070
5050 X1=X/U1
5060 Y1=0
5070 RETURN
5099 REM SUBROUTINE FOR 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 SUBROUTINE FOR XFORMATION 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=COS(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 SUBROUTINE FOR XFORMATION MATRIX V
5500 Q1=V1
5510 Q2=V2
5520 Q5=V5
5530 Q6=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
5580 Q3=V3
5590 Q4=V4
5600 Q7=V7
5610 Q8=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 SUBROUTINE FOR CIRCUIT, MAGNITUDE, AND PHASE
6000 N1=N3/((R2-R1)*L3)
6010 N2=N4/((R4-R3)*L4)
6020 Q0=6.300475204E-7*R5
6030 W1=W*C6*R0
6040 W2=W*C7*R9
6050 W3=1-W1*W2
6060 W4=W1+W2
6070 FOR I=1 TO 3
6080 FOR J=1 TO 5
6090 Z8=Q0*N1*N2*A(I,J)
6100 Z9=Q0*N1*N2*B(I,J)
6110 Z=Q0*N1*N1*C(I,J)
6120 Z2=Q0*N1*N1*(D(I,J)+A3)
6130 Z1=Q0*N2*N2*E(I,J)
6140 Z3=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=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 SUBROUTINE FOR DISC. VOLTRAGE AN PHASE SHIFT
6500 Q1=M(2,5)*SIN(P(2,5))-M(2,1)*SIN(P(2,1))
6510 Q2=-M(2,5)*COS(P(2,5))+M(2,1)*COS(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 Q1=Q3
6556 Q2=V1
6560 FOR I=1 TO 3
6570 FOR J=1 TO 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 SUBROUTINE FOR PRINTING RESULTS
6700 PRINT "DRIVER RES", "INDUCTANCE", "NO TURNS", "SHUNT CAP", "NØR IM PT"
6710 PRINT R6, Q0*N1*N1*A3/W, N3, C6, (D(2,3)+A3)/A3
6720 PRINT "PICKUP RES", "INDUCTANCE", "NO TURNS", "SHUNT CAP", "NØR IM PT"
6730 PRINT R7, Q0*N2*N2*A4/W, N4, C7, (F(2,3)+A4)/A4
6740 PRINT "DRIVING VOLT", "SERIES RES", "AMP GAIN", "INPUT IMP"
6750 PRINT V0, R0, G5, R9
6760 PRINT "DISCRIMINATOR VOLTRAGE IS"; V1
6770 PRINT
6780 PRINT L6, L6+L2, L6+2*L2, L6+3*L2, L6+4*L2
6790 FOR I=1 TO 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 SUBROUTINE FOR AV. PHASE SHIFT AND LIFT-OFF ERROR
7000 Q1=Q(1,1)
7010 Q2=Q(1,1)
7020 FOR J=2 TO 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 Q=Q

```

```

7100 PRINT "PHASE SHIFT"; Q1;"LIFT-OFF"; Q1-Q2;"IN %"; 3100*(Q1-Q2)/Q
7110 PRINT "IN DEGREE"; Q1*P8, (Q1-Q2)*P8
7120 RETURN
7199 REM FOR COIL DESIGN, ATTENUATOR, DRIFT, AND EXIT
7200 PRINT "1 COIL DESIGN 2 ATTEM. DESIGN 3 DRIFT CHECK 4 CON CAL"
7210 INPUT N5
7220 PRINT
72300N N5 G0 TO 7300,8200,8600,9900
7299 REM FOR COIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FOR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 G0 SUB 7510
7360 N3=02
7370 R6=Q9
7380 PRINT "DRIVER"; N3;"TURNS OF #"; G; "WIRE";
7390 PRINT 07; "/LAYER"; Q8; "LAYERS"; R6; "0HM"
7399 REM FOR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
7430 W2=R4
7440 W3=L4
7450 G0 SUB 7510
7460 N4=02
7470 R7=2*Q9
7480 PRINT "PICKUP"; N4;"TURNS EA #"; G; "WIRE";
7490 PRINT 07; "/LAYER"; Q8; "LAYERS"; R7; "0HMS TOTAL"
7500 G0 TO 1140
7509 REM SUBROUTINE FOR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FOR GAGE
7540 G=01
7550 IF G>.5 THEN 7640
7560 Q5=.95*SQR((W2-W1)*W3/Q2)
7570 Q6=1.0371E-5/05
7580 G0=40
7590 G=40+10*(LOG(Q6)-LOG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 G0 TO 7590
7630 G=INT(G)
7639 REM FOR 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*LOG(Q5*1E3)-.43444)*1E-3+Q5
7680 G0 TO 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 FOR ATTENUATOR 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));"BELOW RES";
8330 PRINT SQR(Q1/C6);"OPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELOW RES";
8350 PRINT SQR(Q2/C7);"OPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 G0 T0 1140
8599 REM FOR DRIFTS
8600 PRINT "SYSTEM DRIFT VARIATIONS"
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","% OF RANGE"
8720 IF E1=0 THEN 8770
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 G0 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 G0 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 G0 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 G0 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 G0 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 G0 SUB 9320
9010 R9=R9/(1+E8)
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VOLT",
9050 G0 SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 G0 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 G0 SUB 9300
9160 R5=R5/(1+A2)
9170 G0 T0 7200
9299 REM SUBROUTINE FOR DRIFT
9300 G0 SUB 600
9310 G0 SUB 1500
9320 G0 SUB 6000
9330 Q1=0
9340 FOR I=1 TO 3
9350 FOR J=1 TO 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*Q1/0
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:

<u>Line Number</u>	<u>Constant</u>	<u>Parameter Varied</u>
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.

```
00250      R5 = .08325
00260      R1 = 0.75
00270      R2 = 1.25
00280      L3 = .36
00290      R4 = .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      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.

00010C THIS PROGRAM EVALUATES THE SENSITIVITY TO A CONDUCTIVITY  
 00020C VARIATION IN ANY GIVEN LAYER OF A MULTI-LAYERED  
 00030C MATERIAL  
 00040C COMPLEX BETA0,BETA1,BETA,V,V97,TR,GAMMA,MUT,DRIVER  
 00050C COMPLEX PICKUP,BETAB  
 00060C COMMON X,Z,Q1,P1/B1/BETA0,BETA1  
 00070C COMMON /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7  
 00080C COMMON /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER  
 00090C COMMON /B3/PICKUP,AIR1,AIR2/B4/GAGE,XIN,XOUT  
 00100C COMMON /B4/XLEN,TURNS,N1A,J1,PERLAY,XLAY  
 00110C DIMENSION T(10),U(10),RH0(10),M(10),BETA(10)  
 00120C DIMENSION V(2,2),V97(2,2),TR(2,2),GAMMA(3),DRIVER(3,5)  
 00130C DIMENSION PICKUP(3,5),RL(5),TMAG(3,5),PHASE(3,5)  
 00140C DIMENSION SHIFT(3,5),MUT(3,5),M9(3),BETAB(3)  
 00150C REAL L2,L3,L4,L5,L6,L7,M,M0,M9,N3,N4  
 00160C PI=3.1415926536  
 00170C RAD=180.0/PI  
 00180C  
 00190C  
 00200C  
 00210C  
 00220C JKL=0  
 00230C THE FOLLOWING ARE INPUT DATA FOR THE PARAMETERS OF  
 00240C THE COILS, MATERIAL, AND CIRCUIT  
 00250C R5=.08325  
 00260C R1=.75  
 00270C R2=1.25  
 00280C L3=.36  
 00290C R3=.36  
 00300C R4=.696  
 00310C L4=.096  
 00320C L5=0.0  
 00330C L6=0.1  
 00340C R6=79.36  
 00350C R7=530.5  
 00360C N3=360.  
 00370C N4=410.  
 00380C R0=1.E6  
 00390C R9=1.E6  
 00400C C6=1.E-12  
 00410C C7=1.E-12  
 00420C V0=10.0  
 00430C G5=1.0  
 00440C F=1.0E4  
 00450C L2=0.025  
 00460C N9 IS THE TOTAL NUMBER OF LAYERS, INCLUDING THE COIL  
 00470C ZONE, AND N8 IS THE LAYER WHOSE CONDUCTIVITY VARIES  
 00480C  
 00490C  
 00500C  
 00510C N9=5  
 00520C N8=4  
 00530C IF(N9.LT.2.OR.N8.GE.N9) GO TO 1010  
 00540C DATA RH0/1.E10,3.632,5.393,3.632,1.E10,5\*0./  
 00550C DATA U/5\*1.,5\*0./  
 00560C DATA T/1.E10,2.8E-2,1.94E-1,2.8E-2,1.,5\*0./  
 00570C L7=L3-2.0\*(L4+L5)  
 00580C S W=2.0\*PI\*F

```

00590      IF(JKL.NE.0) G0 T0 15
00600      TYPE 10
00610      10 F0RMA7(1H ,1HN,13X,10HTHICK.(IN),4X,11HR(M-0HM CM),
00620          13X,7HM,SIGMA,7X,1HU)
00630      15 D0 50 I=1,N9
00640          IF(RH0(I).GT.1.0E9) G0 T0 20
00650          M(I)=0.5094*U(I)*F*R5*R5/RH0(I)
00660          G0 T0 25
00670      20 M(I)=0.0
00680      25 IF(JKL.NE.0) G0 T0 50
00690      30 TYPE 40,I,T(I),RH0(I),M(I),U(I)
00700      40 F0RMA7(1H ,I2,12X,1PE12.5,2X,E12.5,2X,E12.5,2X,0PF6.2)
00710      50 C0NTINUE
00720          T(1)=0.0
00730          T(N9)=0.0
00740          MO=.05
00750          D0 52 I=1,3
00760          AI=I
00770      52 M9(I)=M(N8)*(1.0+(AI-2.0)*MO)
00780      IF(JKL.NE.0) G0 T0 105
00790      VAR=100.0*MO
00800C      THE SYSTEM PARAMETERS ARE PRINTED OUT
00810      TYPE 55,N8,VAR
00820      55 F0RMA7(1H ,25HC0NDUCTIVITY VARIATION OF,I3,14HTH LAYER
00830          1 IS +-,F6.2,1H%)
00840          TYPE 470
00850          TYPE 60,R1,R2,L3
00860      60 F0RMA7(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
00870          1F8.5)
00880          TYPE 70,R3,R4,L4
00890      70 F0RMA7(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
00900          1F8.5)
00910          TYPE 80,R5,F
00920      80 F0RMA7(1H ,17HC0IL MEAN RADIUS=,F8.5,7H INCHES,3X,
00930          120H0PERATING FREQUENCY=,1PE12.5)
00940          TYPE 90,L5
00950      90 F0RMA7(1H ,15HPICKUP RECESSED,F8.5)
00960          TYPE 100,L6,L2
00970      100 F0RMA7(1H ,13HMIN LIFT-0FF=,F8.5,3X,19HLIFT-0FF INCREM
00980          1ENT=,F8.5)
00990C      THE INTEGRATION BEGINS HERE. THE MUTUAL,DRIVER,AND
01000C      PICKUP INDUCTANCES AND THE AIR VALUES ARE CALCULATED
01010      105 S1=0.01
01020          S2=5.0
01030          B1=0.0
01040          B2=S2
01050          D0 107 I=1,3
01060          D0 107 J=1,5
01070          MUT(I,J)=(0.0,0.0)
01080          DRIVER(I,J)=(0.0,0.0)
01090      107 PICKUP(I,J)=(0.0,0.0)
01100          AIR1=0.0
01110          AIR2=0.0
01120      110 I1=(B2-B1)/S1
01130          X=B1-S1/2.0
01140          D0 390 IDX=1,I1
01150          X=X+S1

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01160      TEST=X*L3
01170      IF(TEST.GT.20.0) GO TO 120
01180      W3=EXP(-TEST)
01190      GO TO 130
01200 120 W3=0.0
01210 130 W8=1.0-W3
01220      TEST=X*L4
01230      IF(TEST.GT.20.0) GO TO 140
01240      W4=EXP(-TEST)
01250      GO TO 150
01260 140 W4=0.0
01270 150 W9=1.0-W4
01280      TEST=X*L7
01290      IF(TEST.GT.20.0) GO TO 160
01300      W7=EXP(-TEST)
01310      GO TO 170
01320 160 W7=0.0
01330 170 W5=EXP(-X*L5)
01340      W0=1.0-W7*W4
01350      TEST=X*L6
01360      IF(TEST.GT.20.0) GO TO 385
01370      W6=EXP(-2.0*TEST)
01380      Z=X*R2
01390      Q1=R2
01400C     SUBROUTINE BESEL EVALUATES THE INTEGRAL OF XJ1(X)
01410      CALL BESEL(VAL2)
01420      Z=X*R1
01430      Q1=R1
01440      CALL BESEL(VAL1)
01450      Z=X*R4
01460      Q1=R4
01470      CALL BESEL(VAL4)
01480      Z=X*R3
01490      Q1=R3
01500      CALL BESEL(VAL3)
01510      S3=S1*(VAL2-VAL1)*(VAL4-VAL3)
01520      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
01530      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
01540      A5=W6*W5*W8*W9*W0*S3
01550      A6=W6*W8*W8*S4
01560      A7=W6*W5*W5*W9*W9*W0*W0*S5
01570      IF(X.GT.30.0) GO TO 385
01580C     THE LOWEST SIGNIFICANT LAYER,N7,IS DETERMINED
01590      QSUM=0.0
01600      N=N9
01610      TEST=X*X*1.0E-5
01620 180 IF(M(N).LT.TEST) GO TO 190
01630      BETA(N)=CSORT(CMPLX(X*X,M(N)))/U(N)
01640      GO TO 200
01650 190 BETA(N)=CMPLX(X,0.0)
01660 200 QSUM=QSUM+REAL(BETA(N))*T(N)/RS
01670      IF(QSUM.GT.20.0.0R.N.EQ.1) GO TO 210
01680      N=N-1
01690      GO TO 180
01700 210 N7=N
01710      DO 220 I=1,3
01720 220 BETA8(I)=CSORT(CMPLX(X*X,M9(I)))/U(N8)
01730      IF(N8.EQ.N7.0R.N8.EQ.N7+1) GO TO 260

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01740      N=N7+1
01750      BETA0=BETA(N-1)
01760      BETA1=BETA(N)
01770      V(1,2)=BETA1-BETA0
01780      V(2,2)=BETA1+BETA0
01790      N6=N8-1
01800      IF(N8.EQ.N7+2) G0 T0 250
01810      IF(N8.GT.N7) G0 T0 230
01820      N6=N9
01830      IF(N7.EQ.N9-1) G0 T0 300
01840  230 BETA0=BETA(2)
01850      IDX1=N7+2
01860      IF(IDX1.GT.N6) G0 T0 245
01870      D0 240 N=IDX1,N6
01880      BETA1=BETA(N)
01890      JUMP=1
01900      CALL XF0RM(N,TR,R5,U,T)
01910      CALL MATRIX(JUMP,V,TR)
01920  240 BETA0=BETA1
01930  245 IF(N8.LT.N7) G0 T0 300
01940  250 V97(1,2)=V(1,2)
01950      V97(2,2)=V(2,2)
01960  260 IF(N8.EQ.N9-1) G0 T0 300
01970      N=N8+2
01980      BETA0=BETA(N-1)
01990      BETA1=BETA(N)
02000      CALL XF0RM(N,TR,R5,U,T)
02010      D0 270 I=1,2
02020      D0 270 J=1,2
02030  270 V(I,J)=TR(I,J)
02040      IF(N8.EQ.N9-2) G0 T0 290
02050      BETA0=BETA(N8+2)
02060      IDX1=N8+3
02070      IF(IDX1.GT.N9) G0 T0 290
02080      D0 280 N=IDX1,N9
02090      BETA1=BETA(N)
02100      JUMP=0
02110      CALL XF0RM(N,TR,R5,U,T)
02120      CALL MATRIX(JUMP,V,TR)
02130  280 BETA0=BETA1
02140  290 V97(1,1)=V(1,2)
02150      V97(2,1)=V(2,2)
02160  300 D0 330 I=1,3
02170      IF(N8.LT.N7) G0 T0 330
02180      IF(N8.EQ.N7) G0 T0 310
02190      BETA0=BETA(N8-1)
02200      N=N8
02210      BETA1=BETA8(I)
02220      IF(N8.EQ.N7+1) G0 T0 305
02230      CALL XF0RM(N,TR,R5,U,T)
02240      V(1,2)=V97(1,2)
02250      V(2,2)=V97(2,2)
02260      JUMP=1
02270      CALL MATRIX(JUMP,V,TR)
02280      G0 T0 310
02290  305 V(1,2)=BETA1-BETA0
02300      V(2,2)=BETA1+BETA0
02310  310 BETA0=BETA8(I)

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02320      N=N8+1
02330      BETA1=BETA(N)
02340      IF(N8.EQ.N7) GO TO 315
02350      JUMP=1
02360      CALL XFORM(N,TR,R5,U,T)
02370      CALL MATRIX(JUMP,V,TR)
02380      GO TO 320
02390 315 V(1,2)=BETA1-BETA0
02400      V(2,2)=BETA1+BETA0
02410 320 IF(N8.EQ.N9-1) GO TO 330
02420      DO 325 J=1,2
02430      TR(J,1)=V(J,1)
02440 325 TR(J,2)=V97(J,1)
02450      JUMP=1
02460      CALL MATRIX(JUMP,V,TR)
02470 330 GAMMA(I)=V(1,2)/V(2,2)
02480      RL(1)=1.0
02490      TEST=X*L2
02500      IF(TEST.GT.20.0) GO TO 340
02510      W2=EXP(-2.0*TEST)
02520      GO TO 350
02530 340 W2=0.0
02540 350 DO 370 K=2,5
02550      AK=K
02560      TEST=AK*X*L2
02570      IF(TEST.GT.20.0) GO TO 360
02580      RL(K)=W2*RL(K-1)
02590      GO TO 370
02600 360 RL(K)=0.0
02610 370 CONTINUE
02620      DO 380 J=1,3
02630      DO 380 K=1,5
02640      MUT(J,K)=MUT(J,K)+GAMMA(J)*RL(K)*A5
02650      DRIVER(J,K)=DRIVER(J,K)+GAMMA(J)*RL(K)*A6
02660 380 PICKUP(J,K)=PICKUP(J,K)+GAMMA(J)*RL(K)*A7
02670 385 AIR1=AIR1+2.0*S4*(X*L3-W8)
02680      AIR2=AIR2+S5*(4.0*(X*L4-W9)-2.0*W7*W9*W9)
02690 390 CONTINUE
02700      B1=B2
02710      B2=B2+S2
02720      S1=0.05
02730      IF(X.LT.9.0) GO TO 110
02740      S1=0.1
02750      IF(X.LT.29.0) GO TO 110
02760      S1=0.2
02770      IF(X.LT.39.0) GO TO 110
02780      S1=0.5
02790      IF(X.LT.79.0) GO TO 110
02800C      THE INTEGRATION ENDS HERE
02810      IF(JKL.NE.0) GO TO 780
02820C      NEXT, THE INDUCTANCES, VOLTAGES, AND PHASE SHIFTS
02830C      ARE CALCULATED AND PRINTED
02840 400 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
02850      CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
02860      TYPE 410
02870 410 F0RFORMAT(1H ,10H DRIVER RES,4X,10H INDUCTANCE,4X,
02880      18HN0 TURNS,6X,9H SHUNT CAP,5X,9H N0R IM PT)
02890      Q1=Q0*T1*T1*AIR1/W

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02900      Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
02910      Q3=Q0*T2*T2*AIR2/W
02920      Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
02930      TYPE 420,R6,Q1,N3,C6,Q2
02940      420 FORMAT(1H ,1PE12.5,2X,E12.5,2X,OPF8.1,6X,1PE12.5,
02950      12X,OPF9.6)
02960      TYPE 430
02970      430 FFORMAT(1H ,10HPICKUP RES,4X,10HINDUCTANCE,4X,
02980      18HN0 TURNS,6X,9HSHUNT CAP,5X,9HN0R IM PT)
02990      TYPE 420,R7,Q3,N4,C7,Q4
03000      TYPE 440
03010      440 FFORMAT(1H ,12HDRIVING VOLT,2X,10HSERIES RES,4X,
03020      18HAMP GAIN,6X,9HINPUT IMP)
03030      TYPE 450,V0,R0,G5,R9
03040      450 FFORMAT(1H ,F5.1,9X,1PE12.5,2X,OPF8.1,6X,1PE12.5)
03050      TYPE 460,V1
03060      460 FFORMAT(1H ,22HDISCRIMINATOR VOLTAGE=,1PE12.5)
03070      TYPE 470
03080      470 FFORMAT(1H )
03090      RL(1)=L6
03100      D0 480 I=2,5
03110      480 RL(I)=L2+RL(I-1)
03120      TYPE 490,RL
03130      490 FFORMAT(1H ,4(F6.3,8X),F6.3)
03140      TYPE 470
03150      D0 500 I=1,3
03160      TYPE 510,(TMAG(I,J),J=1,5)
03170      TYPE 510,(PHASE(I,J),J=1,5)
03180      TYPE 510,(SHIFT(I,J),J=1,5)
03190      TYPE 470
03200      500 CONTINUE
03210      510 FFORMAT(1H ,4(1PE12.5,2X),E12.5)
03220      CALL SENS SHIFT,RAD,SEN)
03230C     THE USER NEXT SELECTS ONE OF FOUR POSSIBILITIES
03240      520 TYPE 530
03250      530 FFORMAT(' 1 COIL DESIGN  2 ATTEN.DESIGN  3 DRIFT CHECK
03260      1 4 CON CAL')
03270      TYPE 470
03280      ACCEPT 540,N5
03290      540 FFORMAT(I1)
03300      G0 T0(550,680,760,1010),N5
03310C     THE FIRST POSSIBILITY ALLOWS THE USER TO ALTER THE
03320C     COIL DESIGN BY INPUTTING THE REQUESTED INTEGER DATA
03330      550 TYPE 560
03340      560 FFORMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
03350      1 TURNS')
03360      TYPE 470
03370      ACCEPT 570,N1A,N2A,N3A,N4A
03380      570 FFORMAT(4I)
03390      IF(N1A*N2A.EQ.0) G0 T0 580
03400      GAGE=N1A
03410      XIN=R1*R5
03420      XOUT=R2*R5
03430      XLEN=L3*R5
03440      TURNS=N2A
03450      N3=N2A
03460      N1A=-1
03470      J1=1

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03480      CALL GAGER(R6)
03490      G0 T0 600
03500  580 IF(N1A.EQ.0) G0 T0 590
03510      GAGE=N1A
03520      XIN=R1*R5
03530      XOUT=R2*R5
03540      XLEN=L3*R5
03550      J1=1
03560      CALL GAGER(R6)
03570      N3=TURNS
03580      G0 T0 600
03590  590 IF(N2A.EQ.0) G0 T0 620
03600      N3=N2A
03610      TURNS=N2A
03620      XIN=R1*R5
03630      XOUT=R2*R5
03640      XLEN=L3*R5
03650      J1=0
03660      CALL GAGER(R6)
03670  600 TYPE 610,TURNS,GAGE,PERLAY,XLAY,R6
03680  610 FORMAT(1H ,6HDRIVER,F6.1,10H TURNS 0F#,F5.1,4HWIRE,
03690  1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
03700  620 IF(N3A*N4A.EQ.0) G0 T0 630
03710      GAGE=N3A
03720      TURNS=N4A
03730      N4=N4A
03740      XIN=R3*R5
03750      XOUT=R4*R5
03760      XLEN=L4*R5
03770      J1=1
03780      CALL GAGER(R7)
03790      R7=2.0*R7
03800      G0 T0 650
03810  630 IF(N3A.EQ.0) G0 T0 640
03820      GAGE=N3A
03830      XIN=R3*R5
03840      XOUT=R4*R5
03850      XLEN=L4*R5
03860      J1=1
03870      CALL GAGER(R7)
03880      R7=2.0*R7
03890      N4=TURES
03900      G0 T0 650
03910  640 IF(N4A.EQ.0) G0 T0 670
03920      N4=N4A
03930      TURNS=N4A
03940      XIN=R3*R5
03950      XOUT=R4*R5
03960      XLEN=L4*R5
03970      J1=0
03980      CALL GAGER(R7)
03990      R7=2.0*R7
04000  650 TYPE 660,TURNS,GAGE,PERLAY,XLAY,R7
04010  660 FORMAT(1H ,6HPICKUP,F6.1,10H TURNS EA#,F5.1,4HWIRE,
04020  1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
04030  670 G0 T0 400
04040C      THE SECOND POSSIBILITY ALLOWS THE USER TO ALTER THE
04050C      ATTENUATOR DESIGN BY INPUTTING THE DATA REQUESTED IN

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04060C      E FIELD FORMAT
04070      680 TYPE 690
04080      690 FØRMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
04090          1 SHUNT CAP')
04100          TYPE 470
04110          ACCEPT 700,P1,P2,P3,P4
04120      700 FØRMAT(4E)
04130          IF(P1.EQ.0.0) G0 T0 710
04140          R0=P1
04150      710 IF(P2.EQ.0.0) G0 T0 720
04160          C6=P2
04170      720 IF(P3.EQ.0.0) G0 T0 730
04180          R9=P3
04190      730 IF(P4.EQ.0.0) G0 T0 740
04200          C7=P4
04210      740 Q5=1.0/(W*SQRT(Q1*Q2*C6))
04220          Q6=SQRT(Q1*Q2/C6)
04230          Q7=R0/(W*Q1*Q2)
04240          Q8=1.0/(W*SQRT(Q3*Q4*C7))
04250          Q9=SQRT(Q3*Q4/C7)
04260          Q10=R9/(W*Q3*Q4)
04270          TYPE 750,Q5,Q6,Q7
04280      750 FØRMAT(1H ,7HDVR CKT,1PE12.5,10H BELOW RES,1PE12.5,
04290          18H OPT RES,1PE12.5,11H RES/REACT.)
04300          TYPE 755,Q8,Q9,Q10
04310      755 FØRMAT(1H ,7HP-U CKT,1PE12.5,10H BELOW RES,1PE12.5,
04320          18H OPT RES,1PE12.5,11H RES/REACT.)
04330          G0 T0 400
04340C      THE THIRD POSSIBILITY ALLOWS THE USER TO EXAMINE THE
04350C      EFFECT OF DRIFTS ON THE CIRCUIT
04360      760 TYPE 770
04370      770 FØRMAT(1H ,23HSYSTEM DRIFT VARIATIONS)
04380          DR1=0.01
04390          DR2=0.01
04400          DR3=0.01
04410          DR4=0.01
04420          DR5=0.01
04430          DR6=0.01
04440          DR7=0.01
04450          DR8=0.01
04460          DR9=0.01
04470          G0 T0 790
04480      780 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04490          G0 T0 (970,1000),JKL
04500      790 TYPE 800
04510      800 FØRMAT(1H ,11H% VARIATION,3X,13HPARAMETER VAR,1X,
04520          17HRADIANS,7X,7HDEGREES,7X,10HZ OF RANGE)
04530          IF(DR1.EQ.0.0) G0 T0 830
04540          R6=R6*(1.0+DR1)
04550          DR100=100.0*DR1
04560          TYPE 820,DR100
04570      820 FØRMAT(1H ,F4.1,10X,13HDRIVER RES    $)
04580          CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04590          R6=R6/(1.0+DR1)
04600      830 IF(DR2.EQ.0.0) G0 T0 850
04610          R7=R7*(1.0+DR2)
04620          DR100=100.0*DR2
04630          TYPE 840,DR100

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04640 840 F0RMAT(1H ,F4.1,10X,13HPICKUP RES    $)
04650      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04660      R7=R7/(1.0+DR2)
04670 850 IF(DR3.EQ.0.0) G0 T0 870
04680      C6=C6*(1.0+DR3)
04690      DR100=100.0*DR3
04700      TYPE 860,DR100
04710 860 F0RMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
04720      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04730      C6=C6/(1.0+DR3)
04740 870 IF(DR4.EQ.0.0) G0 T0 890
04750      C7=C7*(1.0+DR4)
04760      DR100=100.0*DR4
04770      TYPE 880,DR100
04780 880 F0RMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
04790      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04800      C7=C7/(1.0+DR4)
04810 890 IF(DR5.EQ.0.0) G0 T0 910
04820      R0=R0*(1.0+DR5)
04830      DR100=100.0*DR5
04840      TYPE 900,DR100
04850 900 F0RMAT(1H ,F4.1,10X,13HSERIES RES    $)
04860      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04870      R0=R0/(1.0+DR5)
04880 910 IF(DR6.EQ.0.0) G0 T0 930
04890      R9=R9*(1.0+DR6)
04900      DR100=100.0*DR6
04910      TYPE 920,DR100
04920 920 F0RMAT(1H ,F4.1,10X,13HAMP INPUT RES$)
04930      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04940      R9=R9/(1.0+DR6)
04950 930 IF(DR7.EQ.0.0) G0 T0 950
04960      V0=V0*(1.0+DR7)
04970      DR100=100.0*DR7
04980      TYPE 940,DR100
04990 940 F0RMAT(1H ,F4.1,10X,13HAPPLIED VOLT.$)
05000      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
05010      V0=V0/(1.0+DR7)
05020 950 IF(DR8.EQ.0.0) G0 T0 980
05030      F=F*(1.0+DR8)
05040      DR100=100.0*DR8
05050      TYPE 960,DR100
05060 960 F0RMAT(1H ,F4.1,10X,13HFREQUENCY    $)
05070      JKL=1
05080      G0 T0 5
05090 970 F=F/(1.0+DR8)
05100      JKL=0
05110 980 IF(DR9.EQ.0.0) G0 T0 520
05120      R5=R5*(1.0+DR9)
05130      DR100=100.0*DR9
05140      TYPE 990,DR100
05150 990 F0RMAT(1H ,F4.1,10X,13HMEAN RADIUS   $)
05160      JKL=2
05170      G0 T0 5
05180 1000 R5=R5/(1.0+DR9)
05190      JKL=0
05200      G0 T0 520
05210C     THE FOURTH POSSIBILITY ENDS CALCULATIONS

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05220 1010 CALL EXIT
05230      END
05240      SUBROUTINE BESEL(VAL)
05250      COMMON X,Z,Q1,PI
05260      IF(Z.GT.5.0) GO TO 1510
05270      L=2.0*Z+3.0
05280      F1=0.5*Q1*Q1*Q1
05290      VAL=F1/3.0
05300      DO 1500 I=1,L
05310      AI=I
05320      F1=-F1*0.25*Z*Z/(AI*AI+AI)
05330 1500  VAL=VAL+F1/(2.0*AI+3.0)
05340      GO TO 1520
05350 1510 X0=(-188.1357/Z+109.1142)/Z-23.79333/Z+2.050931/Z
05360      X0=(X0-0.1730503)/Z+0.7034845/Z-0.064109E-3
05370      X1=(-5.817517/Z+2.105874)/Z-.6896196/Z+.4952024/Z
05380      X1=(X1-0.187344E-2)/Z+0.7979095
05390      VAL=(1.0-SQRT(Z)*(X1*COS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
05400      1(X*X*X)
05410 1520 RETURN
05420      END
05430      SUBROUTINE XF0RM(N,TR,R5,U,T)
05440      COMMON /B1/BETA0,BETA1
05450      COMPLEX BETA0,BETA1,EX,TR
05460      DIMENSION EX(2),U(10),T(10),TR(2,2)
05470      EX(1)=CEXP(-BETA0*U(N-1)*T(N-1)/R5)
05480      EX(2)=1.0/EX(1)
05490      DO 1610 I=1,2
05500      DO 1610 J=1,2
05510      K=I+J
05520      IF(K.EQ.3) GO TO 1600
05530      TR(I,J)=(BETA1+BETA0)*EX(J)
05540      GO TO 1610
05550 1600 TR(I,J)=(BETA1-BETA0)*EX(J)
05560 1610 CONTINUE
05570      RETURN
05580      END
05590      SUBROUTINE MATRIX(JUMP,V,TR)
05600      COMPLEX V,Q,TR
05610      DIMENSION Q(2,2),V(2,2),TR(2,2)
05620      IF(JUMP.EQ.1) GO TO 1720
05630      DO 1700 I=1,2
05640 1700 Q(I,1)=V(I,1)
05650      DO 1710 I=1,2
05660      V(I,1)=(0.0,0.0)
05670      DO 1710 J=1,2
05680 1710 V(I,1)=V(I,1)+TR(I,J)*Q(J,1)
05690 1720 DO 1730 I=1,2
05700 1730 Q(I,2)=V(I,2)
05710      DO 1740 I=1,2
05720      V(I,2)=(0.0,0.0)
05730      DO 1740 J=1,2
05740 1740 V(I,2)=V(I,2)+TR(I,J)*Q(J,2)
05750      RETURN
05760      END
05770      SUBROUTINE CIRCT(TMAG,PHASE,QQ,T1,T2)
05780      COMPLEX MUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
05790      COMPLEX DENOM,TNUM,VOLT

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05800 COMMON /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
05810 COMMON /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
05820 COMMON /B3/PICKUP,AIR1,AIR2
05830 DIMENSION MUT(3,5),DRIVER(3,5),PICKUP(3,5)
05840 DIMENSION TMAG(3,5),PHASE(3,5)
05850 REAL L3,L4,N3,N4
05860 T1=N3/((R2-R1)*L3)
05870 T2=N4/((R4-R3)*L4)
05880 Q0=6.300475204E-7*F*R5
05890 Z1=CMPLX(W*C6*R0,-1.0)
05900 Z2=CMPLX(W*C7*R9,-1.0)
05910 Z3=CMPLX(0.0,-R0)
05920 Z4=CMPLX(0.0,-R9)
05930 D0 1800 I=1,3
05940 D0 1800 J=1,5
05950 Z5=Q0*T1*T2*MUT(I,J)
05960 Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(I,J)+AIR1)
05970 Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
05980 DEN0M=Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*(Z2*(Z7+R7)+Z4)
05990 TNUM=V0*R9*G5*(0.0,-1.0)*Z5
06000 VOLT=TNUM/DEN0M
06010 TMAG(I,J)=CABS(VOLT)
06020 1800 PHASE(I,J)=ATAN2(AIMAG(VOLT),REAL(VOLT))
06030 RETURN
06040 END
06050 SUBROUTINE PHASET(A,B,C,V1,03)
06060 DIMENSION A(3,5),B(3,5),C(3,5)
06070 01=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
06080 02=-A(2,5)*COS(B(2,5))-A(2,1)*COS(B(2,1)))
06090 03=ATAN2(01,02)
06100 V1=A(2,1)*SIN(03+B(2,1))
06110 D0 1900 I=1,3
06120 D0 1900 J=1,5
06130 1900 C(I,J)=03-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(I,J)
06140 RETURN
06150 END
06160 SUBROUTINE SENS(0,RAD,01)
06170 DIMENSION 0(3,5)
06180 09=0(1,1)
06190 00=0(1,1)
06200 D0 2010 I=2,5
06210 IF(0(1,1).LT.-09) G0 T0 2000
06220 09=0(1,1)
06230 2000 IF(0(1,1).GT.00) G0 T0 2010
06240 00=0(1,1)
06250 2010 CONTINUE
06260 01=(0(1,1)+0(1,2)+0(1,3)+0(1,4)+0(1,5))/5.0
06270 01=01-(0(3,1)+0(3,2)+0(3,3)+0(3,4)+0(3,5))/5.0
06280 XL0=09-00
06290 PERCT=100.0*XL0/01
06300 DEGR1=01*RAD
06310 DEGR2=XL0*RAD
06320 TYPE 2020,01,XL0,PERCT
06330 2020 F0RMAT(1H ,12HPHASE SHIFT=,1PE12.5,2X,8HL1FT0FF=,
06340 1E12.5,2X,2HZ=,E12.5)
06350 TYPE 2030,DEGR1,DEGR2
06360 2030 F0RMAT(1H ,7HDEGREE:,1PE13.5,5X,E13.5)

```

```

06370      RETURN
06380      END
06390      SUBROUTINE GAGER(RES)
06400      COMMON /B4/G,D1,D2,RLN,T5,N1A,J1,D,E
06410      PI=3.1415926536
06420      IF(J1.EQ.1) GO TO 2120
06430      N1A=-1
06440      D3=0.95*SQRT((D2-D1)*RLN/T5)
06450      X2=1.0371E-5/(D3*D3)
06460      Q=40.0
06470 2100  G=40.0+10.0*(ALOG(X2)-ALOG(.9989+.017*(Q/10.0-1.0))/2.3
06480      10259
06490      IF(ABS(Q-G).LT.1.0E-4) GO TO 2110
06500      Q=G
06510      GO TO 2100
06520 2110  IG=G
06530      G=IG
06540 2120  X2=(.9989+.017*(G/10.0-1.0))*10.0**((G/10.0-4.0)
06550      D3=SQRT(1.0371E-5/X2)
06560      IF(G.GT.40.0) GO TO 2130
06570      X3=(.460655*ALOG(D3*1.0E3)-.43444)*1.0E-3
06580      GO TO 2140
06590 2130  X3=(98.02228*D3+2.56791E-2)*1.0E-3
06600 2140  ID=(RLN/(D3+X3))
06610      D=ID
06620      IE=(D2-D1)/(D3+X3)
06630      E=IE
06640      IF(N1A.EQ.-1) GO TO 2150
06650      TS=D*E
06660 2150  RES=TS*X2*(D2+D1)*PI/12.0
06670      RETURN
06680      END
06690      SUBROUTINE CIRCT1(01,V1,0,RAD,SEN)
06700      DIMENSION 0(3,5),TMAG(3,5),PHASE(3,5)
06710      CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
06720      Q1=0.0
06730      D0 2200 I=1,3
06740      D0 2200 J=1,5
06750      Q2=01-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
06760      1+PHASE(I,J)-0(I,J)
06770      IF(ABS(Q1).GT.ABS(Q2)) GO TO 2200
06780      Q1=Q2
06790 2200  CONTINUE
06800      Q2NEW=RAD*Q1
06810      Q3=100.0*Q1/SEN
06820      TYPE 2210,Q1,Q2NEW,Q3
06830 2210  FORMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
06840      RETURN
06850      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 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      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  $N$ th layer conductor  
in inches,

$K(N)$  = numerical value of resistivity of the  $N$ th layer con-  
ductor in microhm centimeters,

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

the  $(N_9-1)$ 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  $V_0$ , the output voltage of the driving amplifier. For each conductor  $N$ , the value of a dimensionless product  $R_s^2 \omega \mu_N \sigma_N$  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,  $R_0$ , the driver shunt capacitance,  $C_6$ , the amplifier input impedance,  $R_9$ , and the shunt capacitance in the pickup circuit,  $C_7$ , 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:

<u>Parameter</u>	<u>Line Number</u>	<u>Constant</u>
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  $3.632 \mu\Omega\text{-cm}$  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  $5.393 \mu\Omega\text{-cm}$  and a 0.028 in. layer of aluminum with a resistivity of  $3.632 \mu\Omega\text{-cm}$ . 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  $79.36 \Omega$ , and the pickup coils have 410 turns each of No. 54 wire, with a resistance of  $530.5 \Omega$  for both coils. The driver series and the pickup amplifier input resistances are both chosen to be  $1 M\Omega$ . 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  $\pm 5\%$ . 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-0HM 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
CONDUCTIVITY VARIATION OF 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		
COIL MEAN RADIUS 8.32500E-2 INCHES		OPERATING FREQUENCY 10000		
PICK UP RECESSED 0				
MIN LIFT-OFF= 0.1 LIFT-OFF INCREMENT= 0.025				
DRIVER RES	INDUCTANCE	N0 TURNS	SHUNT CAP	N0R IM PT
79.36	6.05067E-4	360	1.00000E-12	0.849616
PICKUP RES	INDUCTANCE	N0 TURNS	SHUNT CAP	N0R IM PT
530.5	4.72124E-4	410	1.00000E-12	0.992308
DRIVING VOLT	SERIES RES	AMP GAIN	INPUT IMP	
10	1000000	1	1000000	
DISCRIMINATOR VOLTAGE 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-OFF 2.66261E-4 IN % 1.03884				
IN DEGREE 1.46852 1.52557E-2				
1 COIL DESIGN 2 ATTEM. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?1</u>				

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 OHM  
 PICKUP 429 TURNS EA # 54 WIRE 11 /LAYER 39 LAYERS 532.582 OHMS TOTAL

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 VOLT	SERIES RES	AMP GAIN	INPUT IMP	
10	1000000	1	1000000	

DISCRIMINATOR VOLTAGE 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-0FF 2.66239E-4 IN % 1.03876				
IN DEGREE 1.46852 1.52544E-2				
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?2</u>				

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	BELOW RES	359.202	OPT RES	13.1225	RES/REACTANCE
P-U CT	10.2505	BELOW RES	330.351	OPT RES	19.2381	RES/REACTANCE
DRIVER RES	INDUCTANCE	N0 TURNS		SHUNT CAP	N0R IM PT	
71.9293	7.13760E-4	391		4.70000E-9	0.849616	
PICKUP RES	INDUCTANCE	N0 TURNS		SHUNT CAP	N0R IM PT	
532.582	5.16896E-4	429		4.70000E-9	0.992308	
DRIVING VOLT	SERIES RES	AMP GAIN		INPUT IMP		
10	500	1		620		

DISCRIMINATOR VOLTAGE 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-0FF 1.26258E-4 IN % 0.496305

IN DEGREE 1.45758 7.23403E-3

1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL

?3

#### SYSTEM DRIFT VARIATIONS

% VARIATN	PARAMETER	RADIAN	DEGREE	% OF 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 VOLT	-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 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON 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 REFLECTION COIL FOR THICKNESS VARIATION OF 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
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
379 REM CIRCUIT DATA
380 R0=1E6
390 R9=1E6
400 C6=1E-12
410 C7=1E-12
420 V0=10.0
430 G5=1
440 F=10E3
450 L2=.025
470 L7=L3-2*(L4+L5)
480 L8=L7+L4
490 L9=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-0HM CM)","M,SIGMA","U"
535 FOR N=1 TO N9
537 READ T(N),R(N),S(N)
539 NEXT N
540 G0 SUB 600
550 FOR N=1 TO N9
560 PRINT N,T(N),R(N),S(N),U(N)
570 NEXT N
580 G0 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 RETURN
750 T(N9)=0
760 T=T(N8)
770 T9=.05

```

```

780 PRINT "THICKNESS VARIATION OF";N8;"TH LAYER IS +-";100*19;"%"
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 COIL DATA
1000 PRINT "R1=";R1,"R2=";R2,"DRIVER LENGTH IS";L3
1010 PRINT "R3=";R3,"R4=";R4,"PICK UP LENGTH IS";L4
1020 PRINT "COIL MEAN RADIUS";R5;"INCHES      OPERATING FREQUENCY";F
1030 PRINT "PICK UP RECESSED";LS
1040 PRINT "MIN LIFT-OFF=";L6;"LIFT-OFF INCREMENT=";L2
1100 REM PROGRAM BEGINS
1110 REM FOR INTEGRATIONS
1120 G0 SUB 1500
1130 REM FOR INDUCTANCES AND CIRCUITS MAGNITUDE AND PHASE
1140 G0 SUB 6000
1150 REM FOR DISCRIMINATOR VOLTAGE AND PHASE SHIFT
1160 G0 SUB 6500
1170 REM FOR PRINTING OF RESULTS
1180 G0 SUB 6700
1190 REM FOR AV. PHASE SHIFT AND LIFT-OFF ERROR
1200 G0 SUB 7000
1400 REM FOR COIL AND ATTENUATOR DESIGNS, AND DRIFT
1410 G0 T0 7200
1499 REM SUBROUTINE FOR INTEGRATION
1500 A3=0
1510 A4=0
1520 FOR I=1 TO 3
1530 FOR J=1 TO 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 FOR X=B1+S1/2 TO B2 STEP S1
1670 G0 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 SUBROUTINE FOR L-FACTOR AND INTEGRANTS

```

```

1999 REM FOR J-FACTOR
2000 G0 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 FOR J=2 TO 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 FOR GAMMA FACTOR
2330 G0 SUB 3200
2340 FOR I=1 TO 3
2350 FOR J=1 TO 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 SUBROUTINE FOR J5=J(R1,R2)/X+3, J6=J(R3,R4)/X+3
2700 R=R1
2710 G0 SUB 2900
2720 J1=02
2730 R=R2
2740 G0 SUB 2900
2750 J5=02-J1

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2760 R=R3
2770 G0 SUB 2900
2780 J3=Q2
2790 R=R4
2800 G0 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 SUBROUTINE 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 T0 Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 G0 T0 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*COS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3198 REM SUBROUTINE FØR GAMMA FØRTOR(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 G0 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 G0 T0 3240
3340 N7=N
3350 REM FØR GAMMA FØRTOR
3360 N=N7+1
3370 G0 SUB 5100
3380 G0 SUB 5150
3390 IF N8=N7+1 THEN 3560
3400 X0=X(N7+1)
3410 Y0=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 T0 N6
3480 X1=X(N)

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3490 Y1=Y(N)
3500 G0 SUB 5300
3510 G0 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 FOR 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 G0 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 FOR N=N8+3 TO N9
3800 X1=X(N)
3810 Y1=Y(N)
3820 G0 SUB 5300
3830 G0 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 FOR 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 FOR I=1 TO 3
3980 IF N8<N7+1 THEN 4190
3990 T(N-1)=T*(1+(I-2)*T9)
4000 G0 SUB 5300
4010 REM FOR T(M+1,M)I,J V(M,1)J>2
4020 V3=I1
4030 V4=I2
4040 V7=I3
4050 V8=I4
4060 G0 SUB 5580

```

```

4070 IF N8=N9-1 THEN 4190
4080 REM FOR V(K,M+1)L,I .....
4090 T1=V1
4100 T2=V2
4110 T3=15
4120 T4=16
4130 T5=V5
4140 T6=V6
4150 T7=17
4160 T8=18
4170 GO SUB 5580
4180 REM FOR GAMMA FACTOR
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 SUBROUTINE FOR BETA(XI,YI)
5000 IF M1<01*1E-5 THEN 5050
5010 Q3=SQR(C2+M1*M1)
5020 X1=.707106781*SQR(Q3+01)/U1
5030 Y1=.707106781*SQR(Q3-01)/U1
5040 GO TO 5070
5050 X1=X/U1
5060 Y1=0
5070 RETURN
5099 REM SUBROUTINE FOR 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 SUBROUTINE FOR XFÖRMATION MATRIX T
5300 Q2=X1+X0
5310 Q1=X1-X0
5320 Q4=Y1+Y0
5330 Q3=Y1-Y0
5340 Q5=II(N-1)*T(N-1)/R5
5350 Q6=EXP(Q5*X0)
5360 Q7=COS(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 SUBROUTINE FOR XFÖRMATION MATRIX V
5500 Q1=V1
5510 Q2=V2

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```

552005=V5
553006=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
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
5999 REM SUBROUTINE FOR CIRCUIT, MAGNITUDE, AND PHASE
6000N1=N3/((R2-R1)*L3)
6010N2=N4/((R4-R3)*L4)
602000=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 FOR I=1 TO 3
6080 FOR J=1 TO 5
6090Z8=00*N1*N2*A(I,J)
6100Z9=00*N1*N2*B(I,J)
6110Z=00*N1*N1*C(I,J)
6120Z22=00*N1*N1*(D(I,J)+A3)
6130Z1=00*N2*N2*E(I,J)
6140Z3=00*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*SGN(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 SUBROUTINE FOR DISC. VOLTAGE AND PHASE SHIFT
6500 Q1=M(2,5)*SIN(P(2,5))-M(2,1)*SIN(P(2,1))
6510 Q2=-M(2,5)*COS(P(2,5))+M(2,1)*COS(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 Q1=Q3
6556 Q2=V1
6560 FOR I=1 TO 3

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6570 FOR J=1 TO 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 SUBROUTINE FOR PRINTING RESULTS
6700 PRINT "DRIVER RES", "INDUCTANCE", "NO TURNS", "SHUNT CAP", "NOR IM PT"
6710 PRINT R6, Q0*N1*N1*A3/W, N3, C6, (D(2,3)+A3)/A3
6720 PRINT "PICKUP RES", "INDUCTANCE", "NO TURNS", "SHUNT CAP", "NOR IM PT"
6730 PRINT R7, Q0*N2*N2*A4/W, N4, C7, (F(2,3)+A4)/A4
6740 PRINT "DRIVING VOLT", "SERIES RES", "AMP GAIN", "INPUT IMP"
6750 PRINT V0, R0, G5, R9
6760 PRINT "DISCRIMINATOR VOLTAGE IS"; V1
6770 PRINT
6780 PRINT L6, L6+L2, L6+2*L2, L6+3*L2, L6+4*L2
6790 FOR I=1 TO 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 SUBROUTINE FOR AV. PHASE SHIFT AND LIFT-OFF ERROR
7000 Q1=Q(1,1)
7010 Q2=Q(1,1)
7020 FOR J=2 TO 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 Q=Q
7100 PRINT "PHASE SHIFT"; Q3;"LIFT-OFF"; Q1-Q2;"IN Z"; 100*(Q1-Q2)/Q
7110 PRINT "IN DEGREE"; Q*P8, (Q1-Q2)*P8
7120 RETURN
7199 REM FOR COIL DESIGN, ATTENUATOR, DRIFT, AND EXIT
7200 PRINT "1 COIL DESIGN 2 ATTN. DESIGN 3 DRIFT CHECK 4 CON CAL"
7210 INPUT N5
7220 PRINT
7230 N5 G0 TO 7300, 8200, 8600, 9900
7299 REM FOR COIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1, Q2, Q3, Q4
7319 REM FOR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 G0 SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER"; N3; "TURNS OF #"; G; "WIRE";
7390 PRINT Q7; "/LAYER"; Q8; "LAYERS"; R6; "0HM"
7399 REM FOR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3

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7430 W2=R4
7440 W3=L4
7450 G0 SUB 7510
7460 N4=02
7470 R7=2*09
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIKE";
7490 PRINT Q7;"/LAYER";Q8;"LAYERS";R7;"OHMS TOTAL"
7500 G0 T0 1140
7509 REM SUBROUTINE FOR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FOR GAGE
7540 G=01
7550 IF G>.5 THEN 7640
7560 Q5=.95*SQR((W2-W1)*W3/02)
7570 Q6=1.0371E-5/Q5/Q5
7580 G0=40
7590 G=40+10*(LOG(Q6)-LOG(.9989+.017*(G0/10-1)))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 G0 T0 7590
7630 G=INT(G)
7639 REM FOR 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*LOG(Q5*1E3)-.43444)*1E-3+Q5
7680 G0 T0 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 FOR ATTENUATOR 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));"BELOW RES";
8330 PRINT SQR(Q1/C6);"OPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELOW RES";
8350 PRINT SQR(Q2/C7);"OPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 G0 T0 1140
8599 REM FOR DRIFTS
8600 PRINT"SYSTEM DRIFT VARIATIONS"
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","% OF RANGE"
8720 IF E1=0 THEN 8770
8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 G0 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 G0 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 G0 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 G0 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 G0 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 G0 SUB 9320
9010 R9=R9/(1+E8)
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VOLT",
9050 G0 SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 G0 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 G0 SUB 9300
9160 R5=R5/(1+A2)
9170 G0 TO 7200
9299 REM SUBROUTINE FOR DRIFT
9300 G0 SUB 600
9310 G0 SUB 1500
9320 G0 SUB 6000

```

```
9330 Q1=0
9340 FOR I=1 TO 3
9350 FOR J=1 TO 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*Q1/0
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:

<u>Line Number</u>	<u>Constant</u>	<u>Parameter Varied</u>
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.

```

00010C THIS PROGRAM EVALUATES THE SENSITIVITY TO A THICKNESS
00020C VARIATION IN ANY GIVEN LAYER OF A MULTI-LAYERED
00030C MATERIAL
00040C COMPLEX BETA0,BETA1,BETA,V,V97,TR,GAMMA,MUT,DRIVER
00050C COMPLEX PICKUP
00060C COMMON X,Z,Q1,PI/B1/BETA0,BETA1
00070C COMMON /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
00080C COMMON /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
00090C COMMON /B3/PICKUP,AIR1,AIR2/B4/GAGE,XIN,XOUT
00100C COMMON /B4/XLEN,TURNS,N1A,J1,PERLAY,XLAY
00110C DIMENSION T(10),U(10),RH0(10),M(10),BETA(10)
00120C DIMENSION V(2,2),V97(2,2),TR(2,2),GAMMA(3),DRIVER(3,5)
00130C DIMENSION PICKUP(3,5),RL(5),TMAG(3,5),PHASE(3,5)
00140C DIMENSION SHIFT(3,5),MUT(3,5)
00150C REAL L2,L3,L4,L5,L6,L7,M,N3,N4
00160C PI=3.1415926536
00170C RAD=180.0/PI
00180C
00190C
00200C
00210C
00220C JKL=0
00230C THE FOLLOWING ARE INPUT DATA FOR THE PARAMETERS OF
00240C THE COILS, MATERIAL, AND CIRCUIT
00250C R5=0.08325
00260C R1=0.75
00270C R2=1.25
00280C L3=0.36
00290C R3=.36
00300C R4=.696
00310C L4=.096
00320C L5=0.0
00330C L6=0.1
00340C R6=79.36
00350C R7=530.5
00360C N3=360.0
00370C N4=410.0
00380C R0=1.0E6
00390C R9=1.0E6
00400C C6=1.0E-12
00410C C7=1.0E-12
00420C V0=10.0
00430C G5=1.0
00440C F=1.0E4
00450C L2=0.025
00460C N9 IS THE TOTAL NUMBER OF LAYERS, INCLUDING THE COIL
00470C ZONE, AND N8 IS THE LAYER WHOSE THICKNESS VARIES
00480C
00490C
00500C
00510C N9=5
00520C N8=4
00530C IF(N9.LT.3.0R.N8.GE.N9.0R.N8.EQ.1) GO TO 1010
00540C DATA RH0/1.E10,3.632,5.393,3.632,1.E10,5*0.0/
00550C DATA U/5*1.0,5*0.0/
00560C DATA T/1.E10,.028,.194,.028,1.,5*0.0/
00570C L7=L3-2.0*(L4+L5)
00580C S W=2.0*PI*F

```

```

00590      IF(JKL.NE.0) G0 T0 15
00600      TYPE 10
00610      10 FORMAT(1H ,1HN,13X,10HTHICK.(IN),4X,11HR(M-0MM CM),
00620          13X,7HM,SIGMA,7X,1HU)
00630      15 D0 50 I=1,N9
00640          IF(RH0(I).GT.1.0E9) G0 T0 20
00650          M(I)=0.5094*U(I)*F*RS*R5/RH0(I)
00660          G0 T0 25
00670      20 M(I)=0.0
00680      25 IF(JKL.NE.0) G0 T0 50
00690      30 TYPE 40,I,T(I),RH0(I),M(I),U(I)
00700      40 FORMAT(1H ,12,12X,1PE12.5,2X,E12.5,2X,0PF6.2)
00710      50 CONTINUE
00720          T(N9)=0.0
00730          T0=T(N8)
00740          T9=0.05
00750      15 IF(JKL.NE.0) G0 T0 105
00760          TVAR=100.0*T9
00770C      THE SYSTEM PARAMETERS ARE PRINTED OUT
00780      TYPE 55,N8,TVAR
00790      55 FORMAT(1H ,22HTHICKNESS VARIATION OF,13,14HTH LAYER
00800          1 IS +-,F6.2,1H%)
00810      TYPE 470
00820      TYPE 60,R1,R2,L3
00830      60 FORMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
00840          1F8.5)
00850      TYPE 70,R3,R4,L4
00860      70 FORMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
00870          1F8.5)
00880      TYPE 80,R5,F
00890      80 FORMAT(1H ,17HC0IL MEAN RADIUS=,F8.5,7H INCHES,3X,
00900          120HOPERATING FREQUENCY=,1PE12.5)
00910      TYPE 90,LS
00920      90 FORMAT(1H ,15HPICKUP RECESSED,F8.5)
00930      TYPE 100,L6,L2
00940      100 FORMAT(1H ,13HMIN LIFT-OFF=,F8.5,3X,19HLIFT-OFF INCREM
00950          1ENT=,F8.5)
00960C      THE INTEGRATION BEGINS HERE. THE MUTUAL,DRIVER,AND
00970C      PICKUP INDUCTANCES AND THE AIR VALUES ARE CALCULATED
00980      105 S1=0.01
00990      S2=5.0
01000      B1=0.0
01010      B2=S2
01020      D0 107 I=1,3
01030      D0 107 J=1,5
01040      MUT(I,J)=(0.0,0.0)
01050      DRIVER(I,J)=(0.0,0.0)
01060      107 PICKUP(I,J)=(0.0,0.0)
01070      AIR1=0.0
01080      AIR2=0.0
01090      110 I1=(B2-B1)/S1
01100      X=B1-S1/2.0
01110      D0 390 IDX=1,II
01120      X=X+S1
01130      TEST=X*L3
01140      IF(TEST.GT.20.0) G0 T0 120
01150      W3=EXP(-TEST)

```

```

01160      G0 T0 130
01170 120 W3=0.0
01180 130 W8=1.0-W3
01190      TEST=X*L4
01200      IF(TEST.GT.20.0) G0 T0 140
01210      W4=EXP(-TEST)
01220      G0 T0 150
01230 140 W4=0.0
01240 150 W9=1.0-W4
01250      TEST=X*L7
01260      IF(TEST.GT.20.0) G0 T0 160
01270      W7=EXP(-TEST)
01280      G0 T0 170
01290 160 W7=0.0
01300 170 W5=EXP(-X*L5)
01310      W0=1.0-W7*W4
01320      TEST=X*L6
01330      IF(TEST.GT.20.0) G0 T0 385
01340      W6=EXP(-2.0*TEST)
01350      Z=X*R2
01360      Q1=R2
01370C     SUBROUTINE BESSEL EVALUATES THE INTEGRAL OF XJ1(X)
01380      CALL BESSEL(VAL2)
01390      Z=X*R1
01400      Q1=R1
01410      CALL BESSEL(VAL1)
01420      Z=X*R4
01430      Q1=R4
01440      CALL BESSEL(VAL4)
01450      Z=X*R3
01460      Q1=R3
01470      CALL BESSEL(VAL3)
01480      S3=S1*(VAL2-VAL1)*(VAL4-VAL3)
01490      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
01500      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
01510      A5=W6*W5*W8*W9*W0*S3
01520      A6=W6*W8*W8*S4
01530      A7=W6*W5*W5*W9*W9*W0*W0*S5
01540      IF(X.GT.30.0) G0 T0 385
01550C     THE LOWEST SIGNIFICANT LAYER,N7, IS DETERMINED
01560      QSUM=0.0
01570      N=N9
01580      TEST=X*X*1.0E-5
01590 180 IF(M(N).LT.TEST) G0 T0 190
01600      BETA(N)=CSQRT(CMPLX(X*X,M(N)))/U(N)
01610      G0 T0 200
01620 190 BETA(N)=CMPLX(X,0.0)
01630 200 QSUM=QSUM+REAL(BETA(N))*T(N)/R5
01640      IF(QSUM.GT.20.0.OR.N.EQ.1) G0 T0 210
01650      N=N-1
01660      G0 T0 180
01670 210 N7=N
01680C     THE MATRIX ELEMENTS V(N7+1,N7)L,2 (L=1,2) ARE
01690C     CALCULATED
01700      V(1,2)=BETA(N+1)-BETA(N)
01710      V(2,2)=BETA(N+1)+BETA(N)
01720C     THE TOTAL MATRIX V(N9,N7) IS CALCULATED BETWEEN HERE

```

```

01730C AND LINE 330. THE GAMMA FACTOR IS JUST THE RATIO
01740C V(N9,N7)1,2/V(N9,N7)2,2. SUBROUTINE XF0RM CALCULATES
01750C THE TRANSFORMATION MATRIX T(M+1,M)I,J AND SUBROUTINE
01760C MATRIX THEN CALCULATES V(K,L)I,J
01770C IF(N8.EQ.(N7+1)) G0 T0 260
01780C BETA0=BETA(N7+1)
01790C N6=N8
01800C IF(N8.GT.(N7+1)) G0 T0 240
01810C N6=N9
01820C 240 IDX1=N7+2
01830C IF(IDX1.GT.N6) G0 T0 255
01840C D0 250 N=IDX1,N6
01850C BETA1=BETA(N)
01860C CALL XF0RM(N,TR,R5,U,T)
01870C JUMP=1
01880C CALL MATRIX(JUMP,V,TR)
01890C 250 BETA0=BETA1
01900C 255 IF(N8.LT.(N7+1)) G0 T0 310
01910C 260 V97(1,2)=V(1,2)
01920C V97(2,2)=V(2,2)
01930C IF(N8.EQ.(N9-1)) G0 T0 300
01940C N=N8+2
01950C BETA0=BETA(N8+1)
01960C BETA1=BETA(N)
01970C CALL XF0RM(N,TR,R5,U,T)
01980C D0 270 I=1,2
01990C D0 270 J=1,2
02000C 270 V(I,J)=TR(I,J)
02010C IF(N8.EQ.(N9-2)) G0 T0 290
02020C BETA0=BETA(N8+2)
02030C IDX1=N8+3
02040C IF(IDX1.GT.N9) G0 T0 290
02050C D0 280 N=IDX1,N9
02060C BETA1=BETA(N)
02070C CALL XF0RM(N,TR,R5,U,T)
02080C JUMP=0
02090C CALL MATRIX(JUMP,V,TR)
02100C 280 BETA0=BETA1
02110C 290 V97(1,1)=V(1,2)
02120C V97(2,1)=V(2,2)
02130C 300 N=N8+1
02140C BETA0=BETA(N8)
02150C BETA1=BETA(N)
02160C 310 D0 330 I=1,3
02170C IF(N8.LT.(N7+1)) G0 T0 330
02180C A1=1
02190C T(N-1)=T0*(1.0+(A1-2.0)*T9)
02200C CALL XF0RM(N,TR,R5,U,T)
02210C V(1,2)=V97(1,2)
02220C V(2,2)=V97(2,2)
02230C JUMP=1
02240C CALL MATRIX(JUMP,V,TR)
02250C IF(N8.EQ.(N9-1)) G0 T0 330
02260C D0 320 J=1,2
02270C TR(J,1)=V(J,1)
02280C 320 TR(J,2)=V97(J,1)
02290C JUMP=1
02300C CALL MATRIX(JUMP,V,TR)

```

```

02310 330 GAMMA(I)=V(1,2)/V(2,2)
02320 T(N8)=T0
02330 RL(1)=1.0
02340 TEST=X*L2
02350 IF(TEST.GT.20.0) G0 T0 340
02360 W2=EXP(-2.0*TEST)
02370 G0 T0 350
02380 340 W2=0.0
02390 350 D0 370 K=2.5
02400 AK=K
02410 TEST=AK*X*L2
02420 IF(TEST.GT.20.0) G0 T0 360
02430 RL(K)=W2*RL(K-1)
02440 G0 T0 370
02450 360 RL(K)=0.0
02460 370 C0NTINUE
02470 D0 380 J=1,3
02480 D0 380 K=1,5
02490 MUT(J,K)=MUT(J,K)+GAMMA(J)*RL(K)*A5
02500 DRIVER(J,K)=DRIVER(J,K)+GAMMA(J)*RL(K)*A6
02510 380 PICKUP(J,K)=PICKUP(J,K)+GAMMA(J)*RL(K)*A7
02520 385 AIR1=AIR1+2.0*S4*(X*L3-W8)
02530 AIR2=AIR2+S5*(4.0*(X*L4-W9)-2.0*W7*W9*W9)
02540 390 C0NTINUE
02550 B1=B2
02560 B2=B2+S2
02570 S1=0.05
02580 IF(X.LT.9.0) G0 T0 110
02590 S1=0.1
02600 IF(X.LT.29.0) G0 T0 110
02610 S1=0.2
02620 IF(X.LT.39.0) G0 T0 110
02630 S1=0.5
02640 IF(X.LT.79.0) G0 T0 110
02650C THE INTEGRATION ENDS HERE
02660 IF(JKL.NE.0) G0 T0 780
02670C NEXT, THE INDUCTANCES, VOLTAGES, AND PHASE SHIFTS
02680C ARE CALCULATED AND PRINTED
02690 400 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
02700 CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
02710 TYPE 410
02720 410 F0RFORMAT(1H ,10H DRIVER RES,4X,10H INDUCTANCE,4X,
02730 18HN0 TURNS,6X,9H SHUNT CAP,5X,9HN0R IM PT)
02740 Q1=Q0*T1*T1*AIR1/W
02750 Q2=(REAL(DRIVER(2,3))+AIR1)/AIR1
02760 Q3=Q0*T2*T2*AIR2/W
02770 Q4=(REAL(PICKUP(2,3))+AIR2)/AIR2
02780 TYPE 420,R6,Q1,N3,C6,Q2
02790 420 F0RFORMAT(1H ,1PE12.5,2X,E12.5,2X,0PF8.1,6X,1PE12.5,
02800 12X,0PF9.6)
02810 TYPE 430
02820 430 F0RFORMAT(1H ,10H PICKUP RES,4X,10H INDUCTANCE,4X,
02830 18HN0 TURNS,6X,9H SHUNT CAP,5X,9HN0R IM PT)
02840 TYPE 420,R7,Q3,N4,C7,Q4
02850 TYPE 440
02860 440 F0RFORMAT(1H ,12H DRIVING VOLT,2X,10H SERIES RES,4X,
02870 18H AMP GAIN,6X,9H INPUT IMP)
02880 TYPE 450,V0,R0,G5,R9

```

```

02890 450 FØRFORMAT(1H ,F5.1,9X,1PE12.5,2X,0PF8.1,6X,1PE12.5)
02900   TYPE 460,V1
02910 460 FØRFORMAT(1H ,22HDISCRIMINATOR VOLTAGE=,1PE12.5)
02920   TYPE 470
02930 470 FØRFORMAT(1H )
02940   RLC(I)=L6
02950   DØ 480 I=2,5
02960 480 RLC(I)=L2+RL(I-1)
02970   TYPE 490,RL
02980 490 FØRFORMAT(1H ,4(F6.3,8X),F6.3)
02990   TYPE 470
03000   DØ 500 I=1,3
03010   TYPE 510,(TMAG(I,J),J=1,5)
03020   TYPE 510,(PHASE(I,J),J=1,5)
03030   TYPE 510,(SHIFT(I,J),J=1,5)
03040   TYPE 470
03050 500 CØNTINUE
03060 510 FØRFORMAT(1H ,4(1PE12.5,2X),E12.5)
03070   CALL SENS(SHIFT,RAD,SEN)
03080C THE USER NEXT SELECTS ONE OF FOUR POSSIBILITIES
03090 520 TYPE 530
03100 530 FØRFORMAT(' 1 COIL DESIGN 2 ATTEN.DESIGN 3 DRIFT CHECK
03110   1 4 CØN CAL')
03120   TYPE 470
03130   ACCEPT 540,NS
03140 540 FØRFORMAT(1I)
03150   GØ TØ(550,680,760,1010),NS
03160C THE FIRST POSSIBILITY ALLOWS THE USER TO ALTER THE
03170C COIL DESIGN BY INPUTTING THE REQUESTED INTEGER DATA
03180 550 TYPE 560
03190 560 FØRFORMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
03200   1 TURNS')
03210   TYPE 470
03220   ACCEPT 570,N1A,N2A,N3A,N4A
03230 570 FØRFORMAT(4I)
03240   IF(N1A*N2A.EQ.0) GØ TØ 580
03250   GAGE=N1A
03260   XIN=R1*R5
03270   XOUT=R2*R5
03280   XLEN=L3*R5
03290   TURNS=N2A
03300   N3=N2A
03310   N1A=-1
03320   J1=1
03330   CALL GAGER(R6)
03340   GØ TØ 600
03350 580 IF(N1A.EQ.0) GØ TØ 590
03360   GAGE=N1A
03370   XIN=R1*R5
03380   XOUT=R2*R5
03390   XLEN=L3*R5
03400   J1=1
03410   CALL GAGER(R6)
03420   N3=TURNS
03430   GØ TØ 600
03440 590 IF(N2A.EQ.0) GØ TØ 620
03450   N3=N2A

```

```

03460      TURNS=N2A
03470      XIN=R1*R5
03480      X0UT=R2*R5
03490      XLEN=L3*R5
03500      J1=0
03510      CALL GAGER(R6)
03520 600 TYPE 610, TURNS, GAGE, PERLAY, XLAY, R6
03530 610 F0RFORMAT(1H ,6H DRIVER, F6.1, 10H TURNS 0F#, F5.1, 4HWIRE,
03540 1F5.1, 6H/LAYER, F5.1, 6H LAYERS, 1PE12.5, 4H0HMS)
03550 620 IF(N3A*N4A.EQ.0) G0 T0 630
03560      GAGE=N3A
03570      TURNS=N4A
03580      N4=N4A
03590      XIN=R3*R5
03600      X0UT=R4*R5
03610      XLEN=L4*R5
03620      J1=1
03630      CALL GAGER(R7)
03640      R7=2.0*R7
03650      G0 T0 650
03660 630 IF(N3A.EQ.0) G0 T0 640
03670      GAGE=N3A
03680      XIN=R3*R5
03690      X0UT=R4*R5
03700      XLEN=L4*R5
03710      J1=1
03720      CALL GAGER(R7)
03730      R7=2.0*R7
03740      N4=TURNS
03750      G0 T0 650
03760 640 IF(N4A.EQ.0) G0 T0 670
03770      N4=N4A
03780      TURNS=N4A
03790      XIN=R3*R5
03800      X0UT=R4*R5
03810      XLEN=L4*R5
03820      J1=0
03830      CALL GAGER(R7)
03840      R7=2.0*R7
03850 650 TYPE 660, TURNS, GAGE, PERLAY, XLAY, R7
03860 660 F0RFORMAT(1H ,6H PICKUP, F6.1, 10H TURNS EA#, F5.1, 4HWIRE,
03870 1F5.1, 6H/LAYER, F5.1, 6H LAYERS, 1PE12.5, 4H0HMS)
03880 670 G0 T0 400
03890C THE SECOND POSSIBILITY ALLOWS THE USER TO ALTER THE
03900C ATTENUATOR DESIGN BY INPUTTING THE DATA REQUESTED IN
03910C E FIELD FORMAT
03920 680 TYPE 690
03930 690 F0RFORMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
03940      1 SHUNT CAP')
03950      TYPE 470
03960      ACCEPT 700,P1,P2,P3,P4
03970 700 F0RFORMAT(4E)
03980      IF(P1.EQ.0.0) G0 T0 710
03990      R0=P1
04000 710 IF(P2.EQ.0.0) G0 T0 720
04010      C6=P2
04020 720 IF(P3.EQ.0.0) G0 T0 730
04030      R9=P3

```

```

04040 730 IF(P4.EQ.0.0) G0 T0 740
04050 C7=P4
04060 740 Q5=1.0/(W*SORT(Q1*Q2*C6))
04070 Q6=SORT(Q1*Q2/C6)
04080 Q7=R0/(W*Q1*Q2)
04090 Q8=1.0/(W*SORT(Q3*Q4*C7))
04100 Q9=SORT(Q3*Q4/C7)
04110 Q10=R9/(W*Q3*Q4)
04120 TYPE 750,Q5,Q6,Q7
04130 750 F0RFORMAT(1H ,7HDVR CKT,1PE12.5,10H BEL0W RES,1PE12.5,
04140 18H OPT RES,1PE12.5,11H RES/REACT.)
04150 TYPE 755,Q8,Q9,Q10
04160 755 F0RFORMAT(1H ,7HP-U CKT,1PE12.5,10H BEL0W RES,1PE12.5,
04170 18H OPT RES,1PE12.5,11H RES/REACT.)
04180 G0 T0 400
04190C THE THIRD POSSIBILITY ALLOWS THE USER TO EXAMINE THE
04200C EFFECT OF DRIFTS ON THE CIRCUIT
04210 760 TYPE 770
04220 770 F0RFORMAT(1H ,23HSYSTEM DRIFT VARIATIONS)
04230 DR1=0.01
04240 DR2=0.01
04250 DR3=0.01
04260 DR4=0.01
04270 DR5=0.01
04280 DR6=0.01
04290 DR7=0.01
04300 DR8=0.01
04310 DR9=0.01
04320 G0 T0 790
04330 780 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04340 G0 T0 (970,1000),JKL
04350 790 TYPE 800
04360 800 F0RFORMAT(1H ,11HZ VARIATION,3X,13HPARAMETER VAR,1X,
04370 17HRADIANS,7X,7HDEGREES,7X,10HZ OF RANGE)
04380 IF(DR1.EQ.0.0) G0 T0 830
04390 R6=R6*(1.0+DR1)
04400 DR100=100.0*DR1
04410 TYPE 820,DR100
04420 820 F0RFORMAT(1H ,F4.1,10X,13HDRIVER RES $)
04430 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04440 R6=R6/(1.0+DR1)
04450 830 IF(DR2.EQ.0.0) G0 T0 850
04460 R7=R7*(1.0+DR2)
04470 DR100=100.0*DR2
04480 TYPE 840,DR100
04490 840 F0RFORMAT(1H ,F4.1,10X,13HPICKUP RES $)
04500 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04510 R7=R7/(1.0+DR2)
04520 850 IF(DR3.EQ.0.0) G0 T0 870
04530 C6=C6*(1.0+DR3)
04540 DR100=100.0*DR3
04550 TYPE 860,DR100
04560 860 F0RFORMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
04570 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04580 C6=C6/(1.0+DR3)
04590 870 IF(DR4.EQ.0.0) G0 T0 890
04600 C7=C7*(1.0+DR4)
04610 DR100=100.0*DR4

```

```

04620      TYPE 880,DR100
04630  880 F0RMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
04640      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04650      C7=C7/(1.0+DR4)
04660  890 IF(DR5.EQ.0.0) G0 T0 910
04670      R0=R0*(1.0+DR5)
04680      DR100=100.0*DR5
04690      TYPE 900,DR100
04700  900 F0RMAT(1H ,F4.1,10X,13HSERIES RES    $)
04710      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04720      R0=R0/(1.0+DR5)
04730  910 IF(DR6.EQ.0.0) G0 T0 930
04740      R9=R9*(1.0+DR6)
04750      DR100=100.0*DR6
04760      TYPE 920,DR100
04770  920 F0RMAT(1H ,F4.1,10X,13HAMP INPUT RESS)
04780      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04790      R9=R9/(1.0+DR6)
04800  930 IF(DR7.EQ.0.0) G0 T0 950
04810      V0=V0*(1.0+DR7)
04820      DR100=100.0*DR7
04830      TYPE 940,DR100
04840  940 F0RMAT(1H ,F4.1,10X,13HAPPLIED VOLT.$)
04850      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04860      V0=V0/(1.0+DR7)
04870  950 IF(DR8.EQ.0.0) G0 T0 980
04880      F=F*(1.0+DR8)
04890      DR100=100.0*DR8
04900      TYPE 960,DR100
04910  960 F0RMAT(1H ,F4.1,10X,13HFREQUENCY      $)
04920      JKL=1
04930      G0 T0 5
04940  970 F=F/(1.0+DR8)
04950      JKL=0
04960  980 IF(DR9.EQ.0.0) G0 T0 520
04970      R5=R5*(1.0+DR9)
04980      DR100=100.0*DR9
04990      TYPE 990,DR100
05000  990 F0RMAT(1H ,F4.1,10X,13HMEAN RADIUS   $)
05010      JKL=2
05020      G0 T0 5
05030 1000 R5=R5/(1.0+DR9)
05040      JKL=0
05050      G0 T0 520
05060C      THE FOURTH POSSIBILITY ENDS CALCULATIONS
05070 1010 CALL EXIT
05080      END
05090      SUBROUTINE BESEL(VAL)
05100      C0MM0N X,Z,Q1,PI
05110      IF(Z.GT.5.0) G0 T0 1510
05120      L=2.0*Z+3.0
05130      F1=0.5*Q1*Q1*Q1
05140      VAL=F1/3.0
05150      D0 1500 I=1,L
05160      AI=I
05170      F1=-F1*0.25*Z*Z/(AI*AI+AI)
05180 1500 VAL=VAL+F1/(2.0*AI+3.0)
05190      G0 T0 1520

```

```

05200 1510 X0=((( -188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
05210   X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
05220   X1=((( -5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
05230   X1=(X1-0.187344E-2)/Z+0.7979095
05240   VAL=(1.0-SQRT(Z)*(X1*COS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
05250   1(X*X*X)
05260 1520 RETURN
05270 END
05280 SUBROUTINE XF0RM(N,TR,R5,U,T)
05290 COMMON /B1/BETA0,BETA1
05300 COMPLEX BETA0,BETA1,EX,TR
05310 DIMENSION EX(2),U(10),T(10),TR(2,2)
05320 EX(1)=CEXP(-BETA0*U(N-1)*T(N-1)/R5)
05330 EX(2)=1.0/EX(1)
05340 DO 1610 I=1,2
05350 DO 1610 J=1,2
05360 K=I+J
05370 IF(K.EQ.3) GO TO 1600
05380 TR(I,J)=(BETA1+BETA0)*EX(J)
05390 GO TO 1610
05400 1600 TR(I,J)=(BETA1-BETA0)*EX(J)
05410 1610 CONTINUE
05420 RETURN
05430 END
05440 SUBROUTINE MATRIX(JUMP,V,TR)
05450 COMPLEX V,Q,TR
05460 DIMENSION Q(2,2),V(2,2),TR(2,2)
05470 IF(JUMP.EQ.1) GO TO 1720
05480 DO 1700 I=1,2
05490 1700 Q(I,1)=V(I,1)
05500 DO 1710 I=1,2
05510 V(I,1)=(0.0,0.0)
05520 DO 1710 J=1,2
05530 1710 V(I,1)=V(I,1)+TR(I,J)*Q(J,1)
05540 1720 DO 1730 I=1,2
05550 1730 Q(I,2)=V(I,2)
05560 DO 1740 I=1,2
05570 V(I,2)=(0.0,0.0)
05580 DO 1740 J=1,2
05590 1740 V(I,2)=V(I,2)+TR(I,J)*Q(J,2)
05600 RETURN
05610 END
05620 SUBROUTINE CIRCT(TMAG,PHASE,Q0,T1,T2)
05630 COMPLEX MUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
05640 COMPLEX DEN0M,TNUM,V0LT
05650 COMMON /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
05660 COMMON /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
05670 COMMON /B3/PICKUP,AIR1,AIR2
05680 DIMENSION MUT(3,5),DRIVER(3,5),PICKUP(3,5)
05690 DIMENSION TMAG(3,5),PHASE(3,5)
05700 REAL L3,L4,N3,N4
05710 T1=N3/((R2-R1)*L3)
05720 T2=N4/((R4-R3)*L4)
05730 Q0=6.300475204E-7*F*R5
05740 Z1=CMPLX(W*C6*R0,-1.0)
05750 Z2=CMPLX(W*C7*R9,-1.0)
05760 Z3=CMPLX(0.0,-R0)
05770 Z4=CMPLX(0.0,-R9)

```

```

05780      D0 1800 I=1,3
05790      D0 1800 J=1,5
05800      Z5=Q0*T1*T2*MUT(I,J)
05810      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(I,J)+AIR1)
05820      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(I,J)+AIR2)
05830      DENOM=Z1*Z2*Z5*Z6+(Z1*(Z6+R6)+Z3)*(Z2*(Z7+R7)+Z4)
05840      TNUM=V0*R9*G5*(0.0,-1.0)*Z5
05850      VOLT=TNUM/DENOM
05860      TMAG(I,J)=CABS(VOLT)
05870 1800 PHASE(I,J)=ATAN2(AIMAG(VOLT),REAL(VOLT))
05880      RETURN
05890      END
05900      SUBROUTINE PHASET(A,B,C,V1,03)
05910      DIMENSION A(3,5),B(3,5),C(3,5)
05920      01=A(2,5)*SIN(B(2,5))-A(2,1)*SIN(B(2,1))
05930      02=-A(2,5)*COS(B(2,5))-A(2,1)*COS(B(2,1))
05940      03=ATAN2(01,02)
05950      V1=A(2,1)*SIN(03+B(2,1))
05960      D0 1900 I=1,3
05970      D0 1900 J=1,5
05980 1900 C(I,J)=03-ATAN2(V1,SQRT(A(I,J)*A(I,J)-V1*V1))+B(I,J)
05990      RETURN
06000      END
06010      SUBROUTINE SENS(0,RAD,01)
06020      DIMENSION 0(3,5)
06030      09=0(1,1)
06040      00=0(1,1)
06050      D0 2010 I=2,5
06060      IF(0(1,I).LT.09) GO TO 2000
06070      09=0(1,I)
06080 2000 IF(0(1,I).GT.00) GO TO 2010
06090      00=0(1,I)
06100 2010 CONTINUE
06110      01=(0(1,1)+0(1,2)+0(1,3)+0(1,4)+0(1,5))/5.0
06120      01=01-(0(3,1)+0(3,2)+0(3,3)+0(3,4)+0(3,5))/5.0
06130      XL0=09-00
06140      PERCT=100.0*XL0/01
06150      DEGR1=01*RAD
06160      DEGR2=XL0*RAD
06170      TYPE 2020,01,XL0,PERCT
06180 2020 F0RMAT(1H ,12HPHASE SHIFT=,1PE12.5,2X,8HLIFT0FF=,
06190      1E12.5,2X,2HZ=,E12.5)
06200      TYPE 2030,DEGR1,DEGR2
06210 2030 F0RMAT(1H ,7HDEGREE:,1PE13.5,5X,E13.5)
06220      RETURN
06230      END
06240      SUBROUTINE GAGER(RES)
06250      COMMON /B4/G,D1,D2,RLN,T5,N1A,J1,D,E
06260      PI=3.1415926536
06270      IF(J1.EQ.1) GO TO 2120
06280      N1A=-1
06290      D3=0.95*SQRT((D2-D1)*RLN/T5)
06300      X2=1.0371E-5/(D3*D3)
06310      Q=40.0
06320 2100 G=40.0+10.0*(ALOG(X2)-ALOG(.9989+.017*(Q/10.0-1.0)))/2.3
06330      10259
06340      IF(ABS(Q-G).LT.1.0E-4) GO TO 2110

```

```

06350      Q=G
06360      G0 T0 2100
06370 2110 IG=G
06380      G=IG
06390 2120 X2=(-.9989+.017*(G/10.0-1.0))*10.0**(G/10.0-4.0)
06400      D3=SQRT(1.0371E-5/X2)
06410      IF(G.GT.40.0) G0 T0 2130
06420      X3=(-.460655*ALOG(D3*1.0E3)-.43444)*1.0E-3
06430      G0 T0 2140
06440 2130 X3=(98.02228*D3+2.56791E-2)*1.0E-3
06450 2140 ID=(RLN/(D3+X3))
06460      D=ID
06470      IE=(D2-D1)/(D3+X3)
06480      E=IE
06490      IF(NIA.EQ.-1) G0 T0 2150
06500      T5=D*E
06510 2150 RES=T5*X2*(D2+D1)*PI/12.0
06520      RETURN
06530      END
06540      SUBROUTINE CIRCT1(Q1,V1,0,RAD,SEN)
06550      DIMENSION 0(3,5),TMAG(3,5),PHASE(3,5)
06560      CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
06570      Q1=0.0
06580      D0 2200 I=1,3
06590      D0 2200 J=1,5
06600      Q2=Q1-ATAN2(V1,SQRT(TMAG(I,J)*TMAG(I,J)-V1*V1))
06610      1+PHASE(I,J)-Q(I,J)
06620      IF(ABS(Q1).GT.ABS(Q2)) G0 T0 2200
06630      Q1=Q2
06640 2200 CONTINUE
06650      Q2NEW=RAD*Q1
06660      Q3=100.0*Q1/SEN
06670      TYPE 2210,Q1,Q2NEW,Q3
06680 2210 F0RFORMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
06690      RETURN
06700      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  $N$ th layer conductor  
in inches,

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

$U(N)$  = numerical value of relative permeability of the  $N$ th  
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 (R6)	INDUCTANCE .....	NO TURNS (N3)	SHUNT CAP (C6)	NOR IM PT .....

PICKUP RES (R7)	INDUCTANCE .....	NO TURNS (N4)	SHUNT CAP (C7)	NOR IM PT .....
DRIVING VOLT (V0)	SERIES RES (R0)	AMP GAIN (G5)	INPUT IMP (R9)	
DISCRIMINATOR VOLTAGE IS .....				
(L6)	(L6+L2)	(L6+2L2)	(L6+3L2)	(L6+4L2)
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....
0	.....	.....	.....	.....
LIFT-OFF= ..... RADIAN OR ..... DEGREES				
DEFECT VOL IS (V5) SHAPE & ORIENTATION FACTOR IS (A0)				
.....				
1 COIL DESIGN	2 ATTEM. 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  $R_s^2 \omega \mu_N \sigma_N$  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,  $R_0$ , the driver shunt capacitance,  $C_6$ , the amplifier input impedance,  $R_9$ , and the shunt capacitance in the pickup circuit,  $C_7$ , 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 present 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:

<u>Parameter</u>	<u>Line Number</u>	<u>Constant</u>
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  $4.99 \mu\Omega\text{-cm}$ . Above the sodium layer, there is a conductor 15 mils thick with a resistivity of  $75 \mu\Omega\text{-cm}$ . Below the sodium layer, there is a very thick material with a resistivity of  $130 \mu\Omega\text{-cm}$ . 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  $59.06 \Omega$ , and the pickup coils have 450 turns each of No. 58 wire with a resistance of  $1067.4 \Omega$  for both coils. The driver series and the pickup amplifier input resistances are both chosen to be  $1 M\Omega$ . The shunt capacitances in both circuits are chosen to be  $1 \text{ pF}$ . 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.<sup>11</sup>

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

```

---

<sup>11</sup>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		
COIL MEAN RADIUS 0.06 INCHES		OPERATING FREQUENCY 100000		
PICK UP RECESSED 0				
MIN LIFT-OFF= 0.05 LIFT-OFF INCREMENT= 0.0125				
DEFECT LOCATED AT R= 0.06 INCHES AND				
Z= 0.005 INCHES BELOW SURFACE OF 2 TH LAYER				
DRIVER RES	INDUCTANCE	NO TURNS	SHUNT CAP	NOR IM PT
59.06	2.22053E-4	252	1.00000E-12	0.827304
PICKUP RES	INDUCTANCE	NO TURNS	SHUNT CAP	NOR IM PT
1067.4	3.20001E-4	450	1.00000E-12	0.991584
DRIVING VOLT	SERIES RES	AMP GAIN	INPUT IMP	
10	1000000	1	1000000	
DISCRIMINATOR VOLTAGE 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-OFF = 1.70328E-4 RADIAN S OR 9.75907E-3 DEGREES				
DEFECT VOL IS 3.03081E-4 SHAPE & ORIENTATION FACTOR IS 1				
-9.42610E-3	-9.44360E-3	-9.45769E-3	-9.46964E-3	-9.47690E-3
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?1</u>				

DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS  
?48,0,58,0

DRIVER 252 TURNS OF # 48 WIRE 12 /LAYER 21 LAYERS 53.1236 OHM				
PICKUP 598 TURNS EA # 58 WIRE 13 /LAYER 46 LAYERS 1344.82 OHMS TOTAL				
DRIVER RES	INDUCTANCE	NO TURNS	SHUNT CAP	NOR IM PT
53.1236	2.22053E-4	252	1.00000E-12	0.827304
PICKUP RES	INDUCTANCE	NO TURNS	SHUNT CAP	NOR IM PT
1344.82	5.65105E-4	598	1.00000E-12	0.991584
DRIVING VOLT	SERIES RES	AMP GAIN	INPUT IMP	
10	1000000	1	1000000	
DISCRIMINATOR VOLTAGE 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-OFF = 1.70335E-4 RADIAN S OR 9.75949E-3 DEGREES				
DEFECT VOL IS 3.03081E-4 SHAPE & ORIENTATION FACTOR IS 1				
-9.42524E-3	-9.44360E-3	-9.45854E-3	-9.46836E-3	-9.47604E-3
1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL				
<u>?2</u>				

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 BELOW RES 1188.75 OPT RES 6.93088 RES/REACTANCE

P-U CT 7.56445 BELOW RES 2663.27 OPT RES 9.37293 KES/REACTANCE

DRIVER RES	INDUCTANCE	NO TURNS	SHUNT CAP	NOR IM PT
53.1236	2.22053E-4	252	1.30000E-10	0.827304
PICKUP RES	INDUCTANCE	NO TURNS	SHUNT CAP	NOR IM PT
1344.82	5.65105E-4	598	7.90000E-11	0.991584
DRIVING VOLT	SERIES RES	AMP GAIN	INPUT IMP	
10	800	1	3300	

DISCRIMINATOR VOLTAGE 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-OFF = 1.41263E-5 RADIANS OR 8.09378E-4 DEGREES

DEFECT VOL IS 3.03081E-4 SHAPE & ORIENTATION FACTOR IS 1

-9.25662E-3 -9.28992E-3 -9.31980E-3 -9.34541E-3 -9.36676E-3

1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON CAL

?3

#### SYSTEM DRIFT VARIATIONS

% VARIATN	PARAMETER	RADIAN	DEGREE	% OF 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 VOLT	-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 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK 4 CON 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 REFLECTION COIL FOR DEFECT OF MULTILAYER CONDUCTORS
40 DIM A(5),B(5),C(5),D(5),E(5),F(5)
50 DIM M(5),P(5),Q(5)
199 REM CONSTANT
200 P9=3.14159
210 P8=180/P9
249 REM COIL 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 CONDUCTOR 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-0HM CM)","M,SIGMA","U"
535 FOR N=1 TO N9
537 READ T(N),R(N),S(N)
539 NEXT N
540 G0 SUB 600
550 FOR N=1 TO N9
560 PRINT N,T(N),R(N),S(N),U(N)
570 NEXT N
580 G0 T0 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 D0=6.0805E-2*F*R5*R5/R(N8)
680 RETURN
750 T(N9)=0
759 REM DATA OF DEFECT POSITION, VOLUME, AND SHAPE & ORIENTATION

```

```

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 COIL DATA
1000 PRINT "R1=";R1,"R2=";R2,"DRIVER LENGTH IS";L3
1010 PRINT "R3=";R3,"R4=";R4,"PICK UP LENGTH IS";L4
1020 PRINT "COIL MEAN RADIUS";R5;"INCHES      OPERATING FREQUENCY";F
1030 PRINT "PICK UP RECESSED";L5
1040 PRINT "MIN LIFT-OFF=";L6;"LIFT-OFF INCREMENT=";L2
1050 PRINT "DEFECT LOCATED AT R=";R8+R5;"INCHES AND"
1060 PRINT "Z=";Z7;"INCHES BELOW SURFACE OF";N8;"TH LAYER"
1100 REM PROGRAM BEGINS
1110 REM FOR INTEGRATIONS
1120 G0 SUB 1500
1129 REM WITH NO DEFECT
1130 REM FOR INDUCTANCES AND CIRCUITS MAGNITUDE AND PHASE
1135 Q=0
1140 G0 SUB 6000
1150 REM FOR DISCRIMINATOR VOLTAGE AND PHASE SHIFT
1160 G0 SUB 6500
1170 REM FOR PRINTING OF RESULTS
1180 G0 SUB 6700
1190 REM FOR LIFT-OFF ERROR
1200 G0 SUB 7000
1210 REM WITH DEFECT
1220 Q=V5*A0*D0
1230 REM FOR MAGNITUDE AND PHASE
1240 G0 SUB 6000
1250 REM FOR PHASE SHIFT
1260 G0 SUB 7070
1400 REM FOR COIL AND ATTENUATOR DESIGNS, AND DRIFT
1410 G0 T0 7200
1499 REM SUBROUTINE FOR INTEGRATION
1500 A3=0
1510 A4=0
1519 REM IN SUBROUTINE FOR INTEGRATION
1520 FOR J=1 TO 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 FOR X=B1+S1/2 TO B2 STEP S1
1670 G0 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 SUBROUTINE FOR L-FACTOR AND INTEGRANTS
1999 REM FOR J-FACTOR
2000 G0 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 SUBROUTINE FOR L-FACTOR AND INTEGRANT
2262 A8=W6*W3*S6
2264 A9=W6*W4*W5*W8*S7
2270 L(1)=1
2280 FOR J=2 TO 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 FOR GAMMA FACTOR
2330 G0 SUB 3200
2340 FOR J=1 TO 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 SUBROUTINE FOR J5=J(R1,R2)/X+3, J6=J(R3,R4)/X+3
2700 R=R1
2710 G0 SUB 2900
2720 J1=Q2
2730 R=R2
2740 G0 SUB 2900
2750 J5=Q2-J1
2760 R=R3
2770 G0 SUB 2900
2780 J3=Q2
2790 R=R4
2800 G0 SUB 2900
2810 J6=Q2-J3
2820 S3=S1*J5*J6
2830 S4=S1*J5*J5
2840 S5=S1*J6*J6
2849 REM IN SUBROUTINE FOR J5, J6, AND J1
2850 G0 SUB 3060
2860 S6=S1*J5*J1
2870 S7=S1*J6*J1
2880 RETURN
2899 REM SUBROUTINE FOR 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 FOR Q=1 TO Q3
2960 Q1=-.25*Z*Z/Q/(Q+1)*Q1
2970 Q2=Q2+Q1/(2*Q+3)
2980 NEXT Q
2990 G0 T0 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*COS(Z-P9/4)-Q1*SIN(Z-P9/4)))/(X*X*X)
3050 RETURN
3059 REM SUBROUTINE FOR 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 GO TO 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*COS(Q2)/SQR(Z)
3180 RETURN
3194 REM SUBROUTINE FOR GAMMA FACTOR (K1,N5) AND
3196 REM FOR DEFECT PART (K2,N6)=SUM(L=1,2) OF
3198 REM V(M,N7)L,2*EXP((-1)(L)*U(M)*BETA(M)*Z)/V(K,N7)2,2
3199 REM FOR 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 GO 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 GO TO 3240
3340 N7=N
3350 REM FOR GAMMA FACTOR
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 FOR N=N7+2 TO N8
3440 X1=X(N)
3450 Y1=Y(N)
3460 GO SUB 5300
3470 GO 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 GO 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 GO TO 3680
3600 IF N8<N7 THEN 3660
3610 T9=Z7
3620 GO 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 G0 T0 3680
3660 V1=V2=0
3670 REM V(N8+1,N9)
3680 FOR N=N7+2 TO N9
3690 X1=X(N)
3700 Y1=Y(N)
3710 G0 SUB 5300
3720 G0 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 SUBROUTINE FOR 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 G0 T0 5070
5050 X1=X/U1
5060 Y1=0
5070 RETURN
5299 REM SUBROUTINE FOR XF0RMATION 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=COS(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 SUBROUTINE FOR XF0RMATION MATRIX V
5500 Q1=V1
5510 Q2=V2
5520 V1=(Q1*X1-Q2*Y1)*2
5530 V2=(Q1*Y1+Q2*X1)*2
5580 Q3=V3
5590 Q4=V4
5600 Q7=V7
5610 Q8=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 SUBROUTINE
5710 C0=U(N)*T9/R5
5720 Q6=EXP(C0*X(N))
5730 Q1=COS(C0*Y(N))
5740 Q2=SIN(C0*Y(N))
5750 RETURN
5999 REM SUBROUTINE FOR CIRCUIT, MAGNITUDE, AND PHASE
6000 N1=N3/((R2-R1)*L3)
6010 N2=N4/((R4-R3)*L4)
602000=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 SUBROUTINE FOR CIRCUIT, MAGNITUDE, AND PHASE
6080 FOR J=1 TO 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 SUBROUTINE FOR DISCRIMINATOR VOLTAGE AND PHASE SHIFT
6500 Q1=M(5)*SIN(P(5))-M(1)*SIN(P(1))
6510 Q2=-M(5)*COS(P(5))+M(1)*COS(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 Q1=Q3
6556 Q2=V1
6570 FOR J=1 TO 5
6580 Q(J)=Q3-ATN(V1/SQR(M(J)*M(J)-V1*V1))+P(J)
6590 NEXT J
6610 RETURN
6699 REM SUBROUTINE FOR PRINTING RESULTS
6700 PRINT "DRIVER RES", "INDUCTANCE", "NO TURNS", "SHUNT CAP", "NOR IM PT"
6710 PRINT R6, Q0*N1*N1*A3/W, N3, C6, (D(3)+A3)/A3
6720 PRINT "PICKUP RES", "INDUCTANCE", "NO TURNS", "SHUNT CAP", "NOR IM PT"
6730 PRINT R7, Q0*N2*N2*A4/W, N4, C7, (F(3)+A4)/A4

```

```

6740PRINT "DRIVING VOLT","SERIES RES","AMP GAIN","INPUT IMP"
6750PRINTV0,R0,G5,R9
6760PRINT "DISCRIMINATOR VOLTAGE IS";V1
6770 PRINT
6780 PRINT L6,L6+L2,L6+2*L2,L6+3*L2,L6+4*L2
6789 REM IN SUBROUTINE FOR 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 SUBROUTINE FOR LIFT-OFF
7000 Q1=Q(1)
7010 FOR J=2 TO 5
7020 IF ABS(Q1)>ABS(Q(J)) THEN 7040
7030 Q1=Q(J)
7040 NEXT J
7050 PRINT "LIFT-OFF =" ;Q1;" RADIANS OR";Q1*P8;"DEGREES"
7060 RETURN
7069 REM SUBROUTINE FOR PHASE SHIFT
7070 PRINT"DEFECT VOL IS";V5;"SHAPE & ORIENTATION FACTOR IS";AO
7080 Q2=0
7090 FOR J=1 TO 5
7100 Q1=Q1-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 O=Q2/5
7150 RETURN
7199 REM FOR COIL DESIGN, ATTENUATOR, DRIFT, AND EXIT
7200PRINT"1 COIL DESIGN 2 ATTEM. DESIGN 3 DRIFT CHECK 4 CON CAL"
7210INPUT NS
7220PRINT
72300N NS G0 T0 7300,8200,8600,9900
7299 REM FOR COIL DESIGN
7300 PRINT "DRIVER WIRE GAGE, TURNS, PICK-UP WIRE GAGE, TURNS"
7310 INPUT Q1,Q2,Q3,Q4
7319 REM FOR DRIVER
7320 W1=R1
7330 W2=R2
7340 W3=L3
7350 G0 SUB 7510
7360 N3=Q2
7370 R6=Q9
7380 PRINT "DRIVER";N3;"TURNS OF #";G;"WIRE";
7390 PRINT Q7;/LAYER;Q8;"LAYERS";R6;"0HM"
7399 REM FOR PICKUP
7400 Q1=Q3
7410 Q2=Q4
7420 W1=R3
7430 W2=R4
7440 W3=L4
7450 G0 SUB 7510
7460 N4=Q2
7470 R7=2*Q9
7480 PRINT "PICKUP";N4;"TURNS EA #";G;"WIRE";
7490 PRINT Q7;/LAYER;Q8;"LAYERS";R7;"0HMS TOTAL"
7500 G0 T0 1135

```

```

7509 REM SUBROUTINE FOR GAGE AND TURN NUMBER
7510 W1=W1*R5
7520 W2=W2*R5
7530 W3=W3*R5
7539 REM FOR GAGE
7540 G=01
7550 IF G>.5 THEN 7640
7560 Q5=.95*SQR((W2-W1)*W3/02)
7570 Q6=1.0371E-5/05/Q5
7580 G0=40
7590 G=40+10*(LOG(Q6)-LOG(.9989+.017*(G0/10-1))/2.30259
7600 IF ABS(G-G0)<1E-4 THEN 7630
7610 G0=G
7620 G0 TO 7590
7630 G=INT(G)
7639 REM FOR 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*LOG(Q5*1E3)-.43444)*1E-3+Q5
7680 G0 TO 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 FOR ATTENUATOR 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));"BELOW RES";
8330 PRINT SQR(Q1/C6);"OPT RES";R0/(W*Q1);"RES/REACTANCE"
8340 PRINT "P-U CT";1/(W*SQR(Q2*C7));"BELOW RES";
8350 PRINT SQR(Q2/C7);"OPT RES";R9/(W*Q2);"RES/REACTANCE"
8360 G0 TO 1135
8599 REM FOR DRIFTS
8600 PRINT"SYSTEM DRIFT VARIATIONS"
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","% OF RANGE"
8720 IF E1=0 THEN 8770

```

```

8730 R6=R6*(1+E1)
8740 PRINT 100*E1,"DRIVER RES",
8750 G0 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 G0 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 G0 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 G0 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 G0 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 G0 SUB 9320
9010 R9=R9/(1+E8)
9020 IF E9=0 THEN 9070
9030 V0=V0*(1+E9)
9040 PRINT 100*E9,"APPLIED VOLT",
9050 G0 SUB 9320
9060 V0=V0/(1+E9)
9070 IF A1=0 THEN 9120
9080 F=F*(1+A1)
9090 PRINT 100*A1,"FREQUENCY",
9100 G0 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 G0 SUB 9300
9160 R5=R5/(1+A2)
9170 G0 T0 7200
9299 REM SUBROUTINE FOR DRIFT
9300 G0 SUB 600
9310 G0 SUB 1500
9315 Q=V5*A0*D0
9320 G0 SUB 6000
9330 Q1=0
9350 FOR J=1 TO 5
9360 Q2=Q1-ATN(Q2/SQR(M(J)*M(J)-Q2*Q2))+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*Q1/0
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:

<u>Line Number</u>	<u>Constant</u>	<u>Parameter Varied</u>
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.

```

00010C THIS PROGRAM EVALUATES THE SENSITIVITY TO A DEFECT
00020C LOCATED IN ANY GIVEN LAYER OF A MULTI-LAYERED MATERIAL
00030      COMPLEX BETA0,BETA1,BETA,V,TR,GAMMA1,GAMMA2,MUT
00040      COMPLEX DRIVER,PICKUP,GH,IJ,EX
00050      COMMON X,Z,Q1,PI/B1/BETA0,BETA1
00060      COMMON /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
00070      COMMON /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
00080      COMMON /B3/PICKUP,AIR1,AIR2/B4/GAGE,XIN,XOUT
00090      COMMON /B4/XLEN,TURNS,N1A,J1,PERLAY,XLAY
00100      COMMON /B3/GH,IJ/B5/V5,A1,DO
00110      DIMENSION T(10),U(10),RH0(10),M(10),BETA(10)
00120      DIMENSION V(2,2),TR(2,2),DRIVER(5)
00130      DIMENSION PICKUP(5),RL(5),TMAG(5),PHASE(5)
00140      DIMENSION SHIFT(5),MUT(5),GH(5),IJ(5)
00150      REAL L2,L3,L4,L5,L6,L7,M,N3,N4
00160      PI=3.1415926536
00170      RAD=180.0/PI
00180C
00190C
00200C
00210C
00220      JKL=0
00230C THE FOLLOWING ARE INPUT DATA FOR THE PARAMETERS OF THE
00240C COIL, MATERIALS, AND CIRCUIT
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
00460C N9 IS THE TOTAL NUMBER OF LAYERS, INCLUDING THE COIL
00470C ZONE, AND N8 IS THE LAYER IN WHICH THE DEFECT IS LOCATED
00480C
00490C
00500C
00510      N9=4
00520      N8=2
00530      IF(N9.LT.2.OR.N8.GE.N9) GO TO 1010
00540      DATA RH0/130.0,4.99,75.0,1.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
00620      5 W=2.0*PI*F
00630      IF(JKL.NE.0) G0 T0 15
00640C THE SYSTEM PARAMETERS ARE PRINTED OUT
00650      TYPE 10
00660      10 F0RMAT(1H ,1X,1HN,13X,10HTHICK.(IN),4X,11HR(M-0HM CM),
00670      1 3X,7HM,SIGMA,9X,1HU)
00680      15 D0 50 I=1,N9
00690      IF(RH0(I).GT.1.0E9) G0 T0 20
00700      M(I)=0.5094*U(I)*F*R5*R5/RH0(I)
00710      G0 T0 25
00720      20 M(I)=0.0
00730      25 IF(JKL.NE.0) G0 T0 50
00740      30 TYPE 40,I,T(I),RH0(I),M(I),U(I)
00750      40 F0RMAT(1H ,I2,12X,1PE12.5,2X,E12.5,2X,E12.5,2X,0PF6.2)
00760      50 C0NTINUE
00770      T(N9)=0.0
00780      D0=6.0805E-2*F*R5*R5/RH0(N8)
00790      IF(JKL.NE.0) G0 T0 105
00800      TYPE 470
00810      TYPE 60,R1,R2,L3
00820      60 F0RMAT(1H ,3HR1=,F8.5,3X,3HR2=,F8.5,3X,14HDRIVER LENGTH=,
00830      1F8.5)
00840      TYPE 70,R3,R4,L4
00850      70 F0RMAT(1H ,3HR3=,F8.5,3X,3HR4=,F8.5,3X,14HPICKUP LENGTH=,
00860      1F8.5)
00870      TYPE 80,R5,F
00880      80 F0RMAT(1H ,17HC0IL MEAN RADIUS=,F8.5,7H INCHES,3X,
00890      120H0PERATING FREQUENCY=,1PE12.5)
00900      TYPE 90,L5
00910      90 F0RMAT(1H ,15HPICKUP RECESSED,F8.5)
00920      TYPE 100,L6,L2
00930      100 F0RMAT(1H ,13HMIN LIFT-OFF=,F8.5,3X,19HLIFT-OFF INCREM
00940      1ENT=,F8.5)
00950      R85=R8*R5
00960      TYPE 103,R85,Z7,N8
00970      103 F0RMAT(1H , 'DEFECT LOCATED AT R=',F9.6,' INCHES AND'/
00980      2 ' Z=',F9.6,' INCHES BELOW SURFACE OF',I2,'TH LAYER')
00990C THE FIRST INTERVAL AND INCREMENT OF THE INTEGRATION
01000C ARE DEFINED
01010      105 S1=0.01
01020      S2=5.0
01030      B1=0.0
01040      B2=S2
01050      D0 107 I=1,5
01060      MUT(I)=(0.0,0.0)
01070      GH(I)=(0.0,0.0)
01080      DRIVER(I)=(0.0,0.0)
01090      IJ(I)=(0.0,0.0)
01100      107 PICKUP(I)=(0.0,0.0)
01110      AIR1=0.0
01120      AIR2=0.0
01130      110 I1=(B2-B1)/S1
01140C THE INTEGRATION IS BY THE TRAPEZOIDAL METHOD, EVALUATING
01150C   AT THE CENTER OF THE INCREMENTAL INTERVAL
01160      X=B1-S1/2.0

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01170C THE INTEGRATION BEGINS HERE
01180      D0 390 IDX=1,II
01190      X=X+S1
01200      TEST=X*L3
01210      IF(TEST.GT.20.0) G0 T0 120
01220      W3=EXP(-TEST)
01230      G0 T0 130
01240      120 W3=0.0
01250      130 W8=1.0-W3
01260      TEST=X*L4
01270      IF(TEST.GT.20.0) G0 T0 140
01280      W4=EXP(-TEST)
01290      G0 T0 150
01300      140 W4=0.0
01310      150 W9=1.0-W4
01320      TEST=X*L7
01330      IF(TEST.GT.20.0) G0 T0 160
01340      W7=EXP(-TEST)
01350      G0 T0 170
01360      160 W7=0.0
01370      170 W5=EXP(-X*L5)
01380      W0=1.0-W7*W4
01390      TEST=X*L6
01400      IF(TEST.GT.20.0) G0 T0 385
01410      W6=EXP(-TEST)
01420      Z=X*R2
01430      Q1=R2
01440      CALL BESEL(VAL2)
01450      Z=X*R1
01460      Q1=R1
01470      CALL BESEL(VAL1)
01480      Z=X*R4
01490      Q1=R4
01500      CALL BESEL(VAL4)
01510      Z=X*R3
01520      Q1=R3
01530      CALL BESEL(VAL3)
01540C RJ1=J1(X*R) IS CALCULATED
01550      ZS=X*R8
01560      IF(ZS.GT.3.0) G0 T0 173
01570      Q1S=ZS*ZS
01580      Q2S=((2.1E-11*Q1S-5.38E-9)*Q1S+6.757E-7)*Q1S
01590      3 -5.42443E-5
01600      Q2S=((Q2S*Q1S+2.60415E-3)*Q1S-6.25E-2)*Q1S+0.5
01610      RJ1=ZS*Q2S
01620      G0 T0 176
01630      173 Q3S=((-1.14604057/ZS+.27617679)/ZS-.20210391)
01640      4 /ZS+4.61835E-3)/ZS
01650      Q3S=((Q3S+.14937)/ZS+4.68E-6)/ZS+.79788456
01660      Q4S=((-21262014/ZS+.19397232)/ZS
01670      5 +6.022188E-2)/ZS-1.7222733E-1)/ZS
01680      Q4S=((Q4S+5.085E-4)/ZS+.37498836)/ZS-2.35619449+ZS
01690      RJ1=Q3S*COS(Q4S)/SQRT(ZS)
01700      176 S3=S1*(VAL2-VAL1)*(VAL4-VAL3)
01710      S4=S1*(VAL2-VAL1)*(VAL2-VAL1)
01720      S5=S1*(VAL4-VAL3)*(VAL4-VAL3)
01730      S6=S1*(VAL2-VAL1)*RJ1
01740      S7=S1*(VAL4-VAL3)*RJ1

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01750      A5=W6*W6*W5*W8*W9*W0*S3
01760      A6=W6*W6*W8*W8*S4
01770      A7=W6*W6*W5*W5*W9*W9*W0*W0*S5
01780      A8=W6*W8*S6
01790      A9=W6*W9*W0*S7
01800C FOR X LARGE THE MATRIX CALCULATIONS ARE BYPASSED
01810      IF(X.GT.30.0) G0 T0 385
01820      QSUM=0.0
01830      N=N9
01840      180 IF(M(N).EQ.0.0) G0 T0 190
01850      BETA(N)=CSQRT(CMPLX(X*X,M(N)))/U(N)
01860      G0 T0 200
01870      190 BETA(N)=CMPLX(X,0.0)
01880      200 QSUM=QSUM+REAL(BETA(N))*T(N)/R5
01890      IF(QSUM.GT.20.0.OR.N.EQ.1) G0 T0 210
01900      N=N-1
01910      G0 T0 180
01920      210 N7=N
01930      V(1,2)=BETA(N+1)-BETA(N)
01940      V(2,2)=BETA(N+1)+BETA(N)
01950      BETA0=BETA(N+1)
01960      IF(N8.LT.(N7+2)) G0 T0 250
01970      N72=N7+2
01980      IF(N72.GT.N8) G0 T0 250
01990      D0 240 N=N72,N8
02000      BETA1=BETA(N)
02010      CALL XF0RM(N,TR,R5,U,T)
02020      JUMP=1
02030      CALL MATRIX(JUMP,V,TR,BETA1)
02040      240 BETA0=BETA1
02050      250 IF(N8.LT.(N7+1)) G0 T0 270
02060      N=N8
02070      EX=CEXP(BETA(N)*(U(N)*(T(N)-Z7)/R5))
02080      V(1,1)=V(1,2)/EX+V(2,2)*EX
02090      IF(N8.LT.(N7+2)) G0 T0 260
02100      N7=N8-1
02110      260 G0 T0 290
02120      270 IF(N8.LT.N7) G0 T0 280
02130      EX=CEXP(BETA(N)*U(N)*Z7/R5)
02140      V(1,1)=2.0*BETA(N+1)/EX
02150      G0 T0 290
02160      280 V(1,1)=(0.0,0.0)
02170      290 N72=N7+2
02180      IF(N72.GT.N9) G0 T0 302
02190      D0 300 N=N72,N9
02200      BETA1=BETA(N)
02210      CALL XF0RM(N,TR,R5,U,T)
02220      JUMP=0
02230      CALL MATRIX(JUMP,V,TR,BETA1)
02240      300 BETA0=BETA1
02250      302 GAMMA1=V(1,2)/V(2,2)
02260      GAMMA2=V(1,1)/V(2,2)
02270      RL(1)=1.0
02280      TEST=X*L2
02290      IF(TEST.GT.20.0) G0 T0 340
02300      W2=EXP(-TEST)
02310      G0 T0 350
02320      340 W2=0.0

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02330 350 D0 370 K=2,5
02340     AK=K
02350     TEST=AK*X*L2
02360     IF(TEST.GT.20.0) G0 T0 360
02370     RL(K)=W2*RL(K-1)
02380     G0 T0 370
02390 360 RL(K)=0.0
02400 370 CONTINUE
02410 D0 380 K=1,5
02420     MUT(K)=MUT(K)+GAMMA1*RL(K)*RL(K)*A5
02430     DRIVER(K)=DRIVER(K)+GAMMA1*RL(K)*RL(K)*A6
02440     PICKUP(K)=PICKUP(K)+GAMMA1*RL(K)*RL(K)*A7
02450C GH AND IJ ARE THE CORRECTIONS TO DRIVER AND PICKUP
02460C IMPEDANCE DUE TO THE DEFECT
02470     GH(K)=GH(K)+GAMMA2*RL(K)*A8
02480 380 IJ(K)=IJ(K)+GAMMA2*RL(K)*A9
02490 385 AIR1=AIR1+2.0*S4*(X*L3-W8)
02500     AIR2=AIR2+S5*(4.0*(X*L4-W9)-2.0*W7*W9*W9)
02510 390 CONTINUE
02520C THE INTEGRATION ENDS; THE NEXT INTERVAL IS TAKEN
02530     B1=B2
02540     B2=B2+S2
02550C FOR X LARGE, THE INTEGRAL CONVERGES FASTER, SO
02560C LARGER STEP SIZES ARE TAKEN
02570     S1=0.05
02580     IF(X.LT.9.0) G0 T0 110
02590     S1=0.1
02600     IF(X.LT.29.0) G0 T0 110
02610     S1=0.2
02620     IF(X.LT.39.0) G0 T0 110
02630     S1=0.5
02640     IF(X.LT.79.0) G0 T0 110
02650     IF(JKL.NE.0) G0 T0 780
02660 400 ODFIND=0.0
02670     CALL CIRCT(TMAG,PHASE,Q0,T1,T2,ODFIND)
02680     CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
02690C THE RESULTS ARE PRINTED
02700     TYPE 410
02710 410 FORMAT(1H ,10H DRIVER RES,4X,10H INDUCTANCE,4X,
02720     18HN0 TURNS,6X,9H SHUNT CAP,5X,9HN0R IM PT)
02730     Q1=Q0*T1*T1*AIR1/W
02740     Q2=(REAL(DRIVER(3))+AIR1)/AIR1
02750     Q3=Q0*T2*T2*AIR2/W
02760     Q4=(REAL(PICKUP(3))+AIR2)/AIR2
02770     TYPE 420,R6,Q1,N3,C6,Q2
02780 420 FORMAT(1H ,1PE12.5,2X,E12.5,2X,0PF8.1,6X,1PE12.5,
02790     12X,0PF9.6)
02800     TYPE 430
02810 430 FORMAT(1H ,10HPICKUP RES,4X,10H INDUCTANCE,4X,
02820     18HN0 TURNS,6X,9H SHUNT CAP,5X,9HN0R IM PT)
02830     TYPE 420,R7,Q3,N4,C7,Q4
02840     TYPE 440
02850 440 FORMAT(1H ,12H DRIVING VOLT,2X,10HSERIES RES,4X,
02860     18HAMP GAIN,6X,9H INPUT IMP)
02870     TYPE 450,V0,R0,G5,R9
02880 450 FORMAT(1H ,F5.1,9X,1PE12.5,2X,0PF8.1,6X,1PE12.5)
02890     TYPE 460,V1
02900 460 FORMAT(1H ,22H DISCRIMINATOR VOLTAGE=,1PE12.5)

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02910      TYPE 470
02920  470 FØRMAT(1H )
02930      RL(1)=L6
02940      D0 480 I=2,5
02950  480 RL(I)=L2+RL(I-1)
02960      TYPE 490,RL
02970  490 FØRMAT(1H ,4(F6.3,8X),F6.3)
02980      TYPE 470
02990C THE VOLTAGE MAGNITUDE, PHASE, AND SHIFT ARE PRINTED
03000      TYPE 510,(TMAG(J),J=1,5)
03010      TYPE 510,(PHASE(J),J=1,5)
03020      TYPE 510,(SHIFT(J),J=1,5)
03030      TYPE 470
03040  510 FØRMAT(1H ,4(1PE12.5,2X),E12.5)
03050      CALL SENS(SHIFT,RAD)
03060C THE EFFECT OF THE DEFECT IS DETERMINED
03070      QDFIND=V5*A1*D0
03080      CALL CIRCT(TMAG,PHASE,Q0,T1,T2,QDFIND)
03090      TYPE 513,V5,A1
03100  513 FØRMAT(1H , 'DEFECT VOL IS',1PE13.6,
03110      9 ' SHAPE AND ORIENTATION FACTOR',E13.6)
03120      TYPE 470
03130      SEN=0.0
03140      D0 516 J=1,5
03150      RM=TMAG(J)
03160      QPRINT=RAD*(SET-ATAN2(V1,SQRT(RM*RM-V1*V1))
03170      6 +PHASE(J)-SHIFT(J))
03180      SEN=SEN+QPRINT/RAD
03190  516 TYPE 518,QPRINT
03200  518 FØRMAT(1H+,1PE12.5,2X$)
03210      SEN=SEN/5.0
03220      TYPE 470
03230C THE USER IS OFFERED THE OPTION OF MAKING VARIOUS
03240C DESIGN CHANGES
03250  520 TYPE 530
03260  530 FØRMAT(1H , '1 COIL DESIGN 2 ATTEN. DESIGN 3 DRIFT CHECK
03270      1 4 CON CAL')
03280      TYPE 470
03290      ACCEPT 540,N5
03300  540 FØRMAT(I1)
03310      G0 T0(550,680,760,1010),N5
03320C IN THE FIRST POSSIBILITY, USER ENTERS INTEGER DATA FOR
03330C FOUR FACTORS; ZERO MEANS NOT CHANGED FROM INITIAL VALUE
03340  550 TYPE 560
03350  560 FØRMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,
03360      1 TURNS')
03370      TYPE 470
03380      ACCEPT 570,N1A,N2A,N3A,N4A
03390  570 FØRMAT(4I)
03400      IF(N1A*N2A.EQ.0) G0 T0 580
03410      GAGE=N1A
03420      XIN=R1*R5
03430      XOUT=R2*R5
03440      XLEN=L3*R5
03450      TURNS=N2A
03460      N3=N2A
03470      N1A=-1
03480      J1=1

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03490      CALL GAGER(R6)
03500      GO TO 600
03510  580 IF(N1A.EQ.0) GO TO 590
03520      GAGE=N1A
03530      XIN=R1*R5
03540      XOUT=R2*R5
03550      XLEN=L3*R5
03560      J1=1
03570      CALL GAGER(R6)
03580      N3=TURNs
03590      GO TO 600
03600  590 IF(N2A.EQ.0) GO TO 620
03610      N3=N2A
03620      TURNs=N2A
03630      XIN=R1*R5
03640      XOUT=R2*R5
03650      XLEN=L3*R5
03660      J1=0
03670      CALL GAGER(R6)
03680  600 TYPE 610,TURNs,GAGE,PERLAY,XLAY,R6
03690  610 FORMAT(1H ,6HDRIVER,F6.1,10H TURNs 0F#,F5.1,4HWIRE,
03700  1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
03710  620 IF(N3A*N4A.EQ.0) GO TO 630
03720      GAGE=N3A
03730      TURNs=N4A
03740      N4=N4A
03750      XIN=R3*R5
03760      XOUT=R4*R5
03770      XLEN=L4*R5
03780      J1=1
03790      CALL GAGER(R7)
03800      R7=2.0*R7
03810      GO TO 650
03820  630 IF(N3A.EQ.0) GO TO 640
03830      GAGE=N3A
03840      XIN=R3*R5
03850      XOUT=R4*R5
03860      XLEN=L4*R5
03870      J1=1
03880      CALL GAGER(R7)
03890      R7=2.0*R7
03900      N4=TURNs
03910      GO TO 650
03920  640 IF(N4A.EQ.0) GO TO 670
03930      N4=N4A
03940      TURNs=N4A
03950      XIN=R3*R5
03960      XOUT=R4*R5
03970      XLEN=L4*R5
03980      J1=0
03990      CALL GAGER(R7)
04000      R7=2.0*R7
04010  650 TYPE 660,TURNs,GAGE,PERLAY,XLAY,R7
04020  660 FORMAT(1H ,6HPICKUP,F6.1,10H TURNs EA#,F5.1,4HWIRE,
04030  1F5.1,6H/LAYER,F5.1,6HLAYERS,1PE12.5,4H0HMS)
04040  670 GO TO 400
04050C THE SECOND POSSIBILITY ACCEPTS E-FIELD DATA FOR FOUR
04060C OTHER PARAMETERS

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04070 680 TYPE 690
04080 690 FORMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
04090   1 SHUNT CAP')
04100   TYPE 470
04110   ACCEPT 700,P1,P2,P3,P4
04120 700 FORMAT(4E)
04130   IF(P1.EQ.0.0) G0 T0 710
04140   R0=P1
04150 710 IF(P2.EQ.0.0) G0 T0 720
04160   C6=P2
04170 720 IF(P3.EQ.0.0) G0 T0 730
04180   R9=P3
04190 730 IF(P4.EQ.0.0) G0 T0 740
04200   C7=P4
04210 740 Q5=1.0/(W*SQRT(Q1*Q2*C6))
04220   Q6=SQRT(Q1*Q2/C6)
04230   Q7=R0/(W*Q1*Q2)
04240   Q8=1.0/(W*SQRT(Q3*Q4*C7))
04250   Q9=SQRT(Q3*Q4/C7)
04260   Q10=R9/(W*Q3*Q4)
04270   TYPE 750,Q5,Q6,Q7
04280 750 FORMAT(1H ,7HDVR CKT,1PE12.5,10H BELOW RES,1PE12.5,
04290   18H OPT RES,1PE12.5,11H RES/REACT.)
04300   TYPE 755,Q8,Q9,Q10
04310 755 FORMAT(1H ,7HP-U CKT,1PE12.5,10H BELOW RES,1PE12.5,
04320   1 8H OPT RES,1PE12.5,11H RES/REACT.)
04330   G0 T0 400
04340C THE THIRD POSSIBILITY EXAMINES THE EFFECTS OF DRIFTS
04350C ON THE SYSTEM
04360 760 TYPE 770
04370 770 FORMAT(1H ,23HSYSTEM DRIFT VARIATIONS)
04380   DR1=0.01
04390   DR2=0.01
04400   DR3=0.01
04410   DR4=0.01
04420   DR5=0.01
04430   DR6=0.01
04440   DR7=0.01
04450   DR8=0.01
04460   DR9=0.01
04470   G0 T0 790
04480 780 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04490   G0 T0 (970,1000),JKL
04500 790 TYPE 800
04510 800 FORMAT(1H ,11HZ VARIATION,3X,13HPARAMETER VAR,1X,
04520   17HRADIANS,7X,7HDEGREES,7X,10HZ OF RANGE)
04530   IF(DR1.EQ.0.0) G0 T0 830
04540   R6=R6*(1.0+DR1)
04550   DR100=100.0*DR1
04560   TYPE 820,DR100
04570 820 FORMAT(1H ,F4.1,10X,13HDRIVER RES $)
04580   CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04590   R6=R6/(1.0+DR1)
04600 830 IF(DR2.EQ.0.0) G0 T0 850
04610   R7=R7*(1.0+DR2)
04620   DR100=100.0*DR2
04630   TYPE 840,DR100
04640 840 FORMAT(1H ,F4.1,10X,13HPICKUP RES $)

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04650      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04660      R7=R7/(1.0+DR2)
04670      850 IF(DR3.EQ.0.0) G0 T0 870
04680      C6=C6*(1.0+DR3)
04690      DR100=100.0*DR3
04700      TYPE 860,DR100
04710      860 F0RFORMAT(1H ,F4.1,10X,13HDVR SHUNT CAP$)
04720      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04730      C6=C6/(1.0+DR3)
04740      870 IF(DR4.EQ.0.0) G0 T0 890
04750      C7=C7*(1.0+DR4)
04760      DR100=100.0*DR4
04770      TYPE 880,DR100
04780      880 F0RFORMAT(1H ,F4.1,10X,13HP-U SHUNT CAP$)
04790      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04800      C7=C7/(1.0+DR4)
04810      890 IF(DR5.EQ.0.0) G0 T0 910
04820      R0=R0*(1.0+DR5)
04830      DR100=100.0*DR5
04840      TYPE 900,DR100
04850      900 F0RFORMAT(1H ,F4.1,10X,13HSERIES RES   $)
04860      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04870      R0=R0/(1.0+DR5)
04880      910 IF(DR6.EQ.0.0) G0 T0 930
04890      R9=R9*(1.0+DR6)
04900      DR100=100.0*DR6
04910      TYPE 920,DR100
04920      920 F0RFORMAT(1H ,F4.1,10X,13HAMP INPUT RESS$)
04930      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
04940      R9=R9/(1.0+DR6)
04950      930 IF(DR7.EQ.0.0) G0 T0 950
04960      V0=V0*(1.0+DR7)
04970      DR100=100.0*DR7
04980      TYPE 940,DR100
04990      940 F0RFORMAT(1H ,F4.1,10X,13HAPPLIED VOLT.$)
05000      CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
05010      V0=V0/(1.0+DR7)
05020      950 IF(DR8.EQ.0.0) G0 T0 980
05030      F=F*(1.0+DR8)
05040      DR100=100.0*DR8
05050      TYPE 960,DR100
05060      960 F0RFORMAT(1H ,F4.1,10X,13HFREQUENCY    $)
05070      JKL=1
05080      G0 T0 5
05090      970 F=F/(1.0+DR8)
05100      JKL=0
05110      980 IF(DR9.EQ.0.0) G0 T0 520
05120      R5=R5*(1.0+DR9)
05130      DR100=100.0*DR9
05140      TYPE 990,DR100
05150      990 F0RFORMAT(1H ,F4.1,10X,13HMEAN RADIUS  $)
05160      JKL=2
05170      G0 T0 5
05180 1000 R5=R5/(1.0+DR9)
05190      JKL=0
05200      G0 T0 520
05210C THE FOURTH POSSIBILITY ENDS CALCULATIONS
05220 1010 CALL EXIT

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05230      END
05240      SUBROUTINE BESEL(VAL)
05250      COMMON X,Z,Q1,PI
05260      IF(Z.GT.5.0) G0 T0 1510
05270      L=2.0*Z+3.0
05280      F1=0.5*Q1*Q1*Q1
05290      VAL=F1/3.0
05300      D0 1500 I=1,L
05310      AI=I
05320      F1=-F1*0.25*Z*Z/(AI*AI+AI)
05330 1500  VAL=VAL+F1/(2.0*AI+3.0)
05340      G0 T0 1520
05350 1510  X0=((-188.1357/Z+109.1142)/Z-23.79333)/Z+2.050931)/Z
05360      X0=((X0-0.1730503)/Z+0.7034845)/Z-0.064109E-3
05370      X1=((-5.817517/Z+2.105874)/Z-.6896196)/Z+.4952024)/Z
05380      X1=(X1-0.187344E-2)/Z+0.7979095
05390      VAL=(1.0-SQRT(Z)*(X1*COS(Z-PI/4.0)-X0*SIN(Z-PI/4.0)))/
05400      1(X*X*X)
05410 1520  RETURN
05420      END
05430      SUBROUTINE XF0RM(N,TR,R5,U,T)
05440      COMMON /B1/BETA0,BETA1
05450      COMPLEX BETA0,BETA1,EX,TR
05460      DIMENSION EX(2),U(10),T(10),TR(2,2)
05470      EX(1)=CEXP(-BETA0*U(N-1)*T(N-1)/R5)
05480      EX(2)=1.0/EX(1)
05490      D0 1610 I=1,2
05500      D0 1610 J=1,2
05510      K=I+J
05520      IF(K.EQ.3) G0 T0 1600
05530      TR(I,J)=(BETA1+BETA0)*EX(J)
05540      G0 T0 1610
05550 1600  TR(I,J)=(BETA1-BETA0)*EX(J)
05560 1610  CONTINUE
05570      RETURN
05580      END
05590      SUBROUTINE MATRIX(JUMP,V,TR,BETA1)
05600      COMPLEX V,Q,TR,BETA1
05610      DIMENSION Q(2,2),V(2,2),TR(2,2)
05620      IF(JUMP.EQ.1) G0 T0 1720
05630      Q(1,1)=V(1,1)
05640      V(1,1)=2.0*BETA1*Q(1,1)
05650 1720  D0 1730 I=1,2
05660 1730  Q(I,2)=V(I,2)
05670      D0 1740 I=1,2
05680      V(I,2)=(0.0,0.0)
05690      D0 1740 J=1,2
05700 1740  V(I,2)=V(I,2)+TR(I,J)*Q(J,2)
05710      RETURN
05720      END
05730      SUBROUTINE CIRCT(TMAG,PHASE,Q0,T1,T2,Q)
05740      COMPLEX MUT,DRIVER,PICKUP,Z1,Z2,Z3,Z4,Z5,Z6,Z7
05750      COMPLEX DEN0M,TNUM,VOLT,GH,IJ
05760      COMMON /B2/R1,R2,R3,R4,L3,L4,R0,R6,R7,R9,C6,C7
05770      COMMON /B2/V0,G5,W,F,R5,N3,N4/B3/MUT,DRIVER
05780      COMMON /B3/PICKUP,AIR1,AIR2,GH,IJ
05790      DIMENSION MUT(5),DRIVER(5),PICKUP(5)
05800      DIMENSION TMAG(5),PHASE(5),GH(5),IJ(5)

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05810      REAL L3,L4,N3,N4
05820      T1=N3/((R2-R1)*L3)
05830      T2=N4/((R4-R3)*L4)
05840      Q0=6.300475204E-7*F*R5
05850      Z1=CMPLX(W*R0*C6,-1.0)
05860      Z2=CMPLX(W*R9*C7,-1.0)
05870      Z3=CMPLX(0.0,-R0)
05880      Z4=CMPLX(0.0,-R9)
05890      D0 1800 J=1,5
05900      Z5=Q0*T1*T2*(MUT(J)+0*(0.0,-1.0)*GH(J)*IJ(J))
05910      Z6=Q0*T1*T1*(0.0,1.0)*(DRIVER(J)+AIR1+Q*GH(J)*GH(J))
05920      Z7=Q0*T2*T2*(0.0,1.0)*(PICKUP(J)+AIR2+Q*IJ(J)*IJ(J))
05930      DENOM=Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*(Z2*(Z7+R7)+Z4)
05940      TNUM=V0*R9*G5*(0.0,-1.0)*Z5
05950      VOLT=TNUM/DENOM
05960      TMAG(J)=CABS(VOLT)
05970 1800 PHASE(J)=ATAN2(AIMAG(VOLT),REAL(VOLT))
05980      RETURN
05990      END
06000      SUBROUTINE PHASET(A,B,C,V1,03)
06010      DIMENSION A(5),B(5),C(5)
06020      01=A(5)*SIN(B(5))-A(1)*SIN(B(1))
06030      02=-A(5)*COS(B(5))-A(1)*COS(B(1)))
06040      03=ATAN2(01,02)
06050      V1=A(1)*SIN(03+B(1))
06060      D0 1900 J=1,5
06070 1900 C(J)=03-ATAN2(V1,SQRT(A(J)*A(J)-V1*V1))+B(J)
06080      RETURN
06090      END
06100      SUBROUTINE SENS(0,RAD)
06110      DIMENSION 0(5)
06120      02=0.0
06130      D0 2000 J=1,5
06140      01=0(J)
06150      IF(ABS(02).GT.ABS(01)) G0 T0 2000
06160      02=01
06170 2000 CONTINUE
06180      02DEG=02*RAD
06190      TYPE 2010,Q2,Q2DEG
06200 2010 FORMAT(1H , 'LIFT-OFF=',1PE13.6,' RADIANS OR',
06210      6 E13.6,' DEGREES')
06220      RETURN
06230      END
06240      SUBROUTINE GAGER(RES)
06250      COMMON /B4/G,D1,D2,RLN,T5,N1A,J1,D,E
06260      PI=3.1415926536
06270      IF(J1.EQ.1) G0 T0 2120
06280      N1A=-1
06290      D3=0.95*SQRT((D2-D1)*RLN/T5)
06300      X2=1.0371E-5/(D3*D3)
06310      Q=40.0
06320 2100 G=40.0+10.0*(ALOG(X2)-ALOG(.9989+.017*(Q/10.0-1.0))/2.3
06330      10259
06340      IF(ABS(Q-G).LT.1.0E-4) G0 T0 2110
06350      Q=G
06360      G0 T0 2100

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06370 2110 IG=G
06380   G=IG
06390 2120 X2=(.9989+.017*(G/10.0-1.0))*10.0**(G/10.0-4.0)
06400   D3=SQRT(1.0371E-5/X2)
06410   IF(G.GT.40.0) G0 T0 2130
06420   X3=(-.460655*ALOG(D3*1.0E3)-.43444)*1.0E-3
06430   G0 T0 2140
06440 2130 X3=(98.02228*D3+2.56791E-2)*1.0E-3
06450 2140 ID=(RLN/(D3+X3))
06460   D=ID
06470   IE=(D2-D1)/(D3+X3)
06480   E=IE
06490   IF(N1A.EQ.-1) G0 T0 2150
06500   TS=D*E
06510 2150 RES=TS*X2*(D2+D1)*PI/12.0
06520   RETURN
06530   END
06540   SUBROUTINE CIRCT1(Q1,V1,0,RAD,SEN)
06550   COMMON /BS/V5,A1,D0
06560   DIMENSION Q(5),TMAG(5),PHASE(5)
06570   QDFIND=V5*A1*D0
06580   CALL CIRCT(TMAG,PHASE,Q0,T1,T2,QDFIND)
06590   Q1=0.0
06600   D0 2200 J=1,5
06610   Q2=Q1-ATAN2(V1,SQRT(TMAG(J)*TMAG(J)-V1*V1))
06620   1+PHASE(J)-Q(J)
06630   IF(ABS(Q1).GT.ABS(Q2)) G0 T0 2200
06640   Q1=Q2
06650 2200 CONTINUE
06660   Q2NEW=RAD*Q1
06670   Q3=100.0*Q1/SEN
06680   TYPE 2210,Q1,Q2NEW,Q3
06690 2210 FORMAT(1H+,1X,2(1PE12.5,2X),1PE12.5)
06700   RETURN
06710   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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