An Automated Immittance Measuring System for Electroacoustic Transducers

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An Automated Measuring System for Electroacoustic Transducers

A fully automated method of obtaining immittance loops of piezoelectric transducers has been designed to be utilized in conjunction with the Hewlett-Packard 4192A Impedance Analyzer. The algorithm determines the frequencies at maximum and minimum immittances, the series and parallel resonance frequencies, and the resonance and antiresonance frequencies as well as the mechanical quality factor of the element under test. The collected data are plotted in the form of either admittance or impedance loops with evenly spaced points. The program has been implemented successfully as a means to rapidly obtain the admittance information of various loaded and unloaded transducers and transducer elements.
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AN AUTOMATED MEASURING SYSTEM FOR ELECTROACOUSTIC TRANSDUCERS

INTRODUCTION

The precise measurement of immittance is a valuable tool for the analysis of electroacoustic transducers and piezoelectric materials. Immittance is used in the determination of transducer efficiency, electrical matching, and the tuning and analysis of transducer performance and of material parameters of active transducer materials. Previous techniques for immittance measurements involved the use of such devices as impedance bridges, analog voltmeters, phase meters, and some special analog devices like the vector impedance meter. All of the before mentioned devices suffer from one or more restrictions; e.g., speed, precision, or stability.

The HP Model 4192A Digital Network Analyzer is computer controlled and has the ability to make immittance measurements at high speed with excellent precision and stability. Combined with the developed circular approximation algorithm, the measurements can be made with greater efficiency to provide the maximum amount of information with the minimum number of data points. This method also allows for fast, accurate computation of critical points of immittance without knowing the series (parallel) resonance of the transducer. The optimization of data points is achieved by the determination of frequencies that will be quasi-uniformly distributed around the immittance circle as opposed to the "clustering" of frequencies above and below the frequency of maximum immittance.

Figure 1 compares an immittance circle defined by a linear sequence of frequencies with one in which the frequencies are generated from the circular approximation method. There are two hundred points in the linear frequency sweep of Fig. 1a and only fifty points in Fig. 1b. This circular approximation method has been implemented on various piezoelectric transducers and works exceptionally well in most cases. The timesaving is greatest when measuring high-Q transducers. Linear-spaced frequency points appear diluted on the steep slopes of the imaginary part of a high-Q immittance, as shown in Fig. 2. For low-Q curves the frequency distribution is more evenly spaced. When the data are presented in the form of imaginary verses real immittance, the data from high-Q systems are
Fig. 1a - Immittance loop showing the distribution of data points resulting from a linear sweep of two hundred frequency steps.

Fig. 1b - Immittance loop showing the more uniform distribution of only 50 data points when frequencies are determined by the circular approximation method.

Fig. 2 - Distribution of data points for equally spaced frequencies on the imaginary part of the immittance curve for a high-Q system and for a low-Q system.
concentrated near the beginning and end of the immittance circle. For low-
Q systems the data points approach a uniform distribution.

CIRCULAR APPROXIMATION ALGORITHM

The circular approximation method can be applied to admittance and
impedance loops. Because of the similarity of application to impedance and
admittance, and to avoid writing "impedance or admittance", the two
quantities are implied when the term immittance is used in the following
text. The differences between the admittance terms and the impedance terms
will be discussed in the PROGRAM section of this report. Throughout this
report the word "points" appears many times with various meanings. To
assure clarity three symbols are defined:

- The term "points(f)" refers to a frequency.
- The term "points(c)" refers to the ordered pair
  on the the theoretical circle.
- The term "points(i)" refers to the real and
  imaginary position on the immittance loop.

The method presented here will be based on the following equation:

\[ \tan(\theta) = \frac{L \left[ \omega^2 - \omega_i^2 \right]}{\omega R}. \]  \[ [1] \]

This equation is derived [1] from a simple equivalent circuit of a
piezoelectric resonator, where \( L \) is the inductance, \( \omega \) is the angular
frequency, \( \omega_i \) is a resonant frequency (series resonance when measuring
admittance, parallel resonance when measuring impedance), \( \theta \) is the phase
angle, and \( R \) is the resistance. Cady uses \( \omega_0 \) (angular frequency of zero
crossing) in Eq. (1) instead of \( \omega_i \). But \( \omega_i \) is also an angular frequency at
a zero crossing since a transformation of axes is performed with the
circular approximation method. It is algebraically convenient to write
Eq. (1) in the following form: Given \( \omega, R, \) and \( \theta \) for three points(f), \( \omega_i \)
and L are determined by applying Cramer's rule [2] to this expression:

\[ \omega_1^2 + \frac{1}{L} \omega \tan(\Theta) = \omega^2. \] [2]

By using the following equation

\[ L \omega^2 - L \omega_1^2 - \omega \tan(\Theta) = 0, \] [3]

the angular frequencies (\(\omega\)) are determined as a function of the angle \(\Theta\) by solving the quadratic equation. Equations (2) and (3) are the key equations used in the circle approximation method and will be referred to many times in the text of this paper. The argument used for applying Eqs. (1) through (3) to both impedance and admittance is found in Appendix A.

The algorithm used in determining the admittance or impedance loops consists of two major parts. First, the "best fit" circle that approximates the immittance loop is determined from parameters of the simple equivalent circuit of a piezoelectric resonator. Secondly, the circular approximation is then divided into equal arcs that are used to determine quasi-equally spaced points(i) on the immittance loop.

To determine the "best-fit" circle, one must first identify any three frequency points(f) on the immittance loop with the abscissa and ordinate identified as conductance and susceptance (or resistance and reactance), respectively. If previous knowledge exists about the transducer to be measured, these three points(f) are easy to identify. If however, there is no previous knowledge about the transducer, the program will assist the user in determining the three points(f).

The HP 4192 Impedance Analyzer measures the real and imaginary parts of immittance at each of these frequency points(f) and the ordered pairs of data are stored as \((x_i, y_i)\), where \(i\) goes from 1 to 3 corresponding to each of the three frequency points(f). These ordered pairs are used in the general form of the equation of a circle:
\[ x_1 D + y_1 E + F = \left[ x_1^2 + y_1^2 \right] \]  \hspace{1cm} \text{(4)}

of center \([\frac{-D}{2}, \frac{-E}{2}]\) and radius \(\frac{1}{2} \left[ D^2 + E^2 - 4F \right]^{1/2} \). \hspace{1cm} \text{(5)}

To find D, E, and F, we impose the condition that the coordinates of each of the given points satisfy Eq. (4). When these values for D, E, and F are substituted in Eq. (5), we have the radius and center of the circle through the given points. By using the calculated radius and center, two points located 120 degrees from a fixed initial point are found as shown by the boxes in Fig. 1. The authors have arbitrarily chosen the fixed point to be the second initial point. One may use any initial point as long as it remains consistent throughout the entire procedure.

In order that this procedure apply both to loaded and unloaded transducers, a translation of axes is performed on all points used in Eqs. (2) and (3). The formulas for the translation of axes are:

\[ x_t = x_o - x_c + r \quad \text{and} \quad y_t = y_o - y_c \] \hspace{1cm} \text{(6)}

where \((x_c + r, y_c)\) is the new origin. The ordered pair \((x_c, y_c)\) is the center of the circle, \(r\) is the radius, \((x_o, y_o)\) are the old coordinates, and \((x_t, y_t)\) are the old coordinates with the new origin. The slope \([\tan(\theta)]\) is determined by first applying Eqs. (6) to a given point. The resistance \(R\), also found in the Eqs. (2) and (3), is replaced by the diameter or reciprocal of the diameter of the circle depending on which immittance loop is chosen. The quantities \(\omega_1\) and \(L\) are calculated using Eq. (2) and the data of two initial points along with information from the circle. With the calculated parameters \((\omega_1, L, \theta)\) of the two 120-degree points, the frequencies \((\omega/2\pi)\) at the 120-degree points are calculated by applying Eq. (3). The HP 4192 Impedance Analyzer measures the conductance and susceptance (or resistance and reactance) at each frequency, and the points are stored. These points are illustrated by the "triangles" in Fig. 3.
Now a new circle is calculated using the two 120-degree points (c) and the second initial point (i&c). Note that this new circle will be a better approximation to the immittance loop than was the previous one. This procedure iterates until two successive circles are within the desired tolerance. The result of this convergence is a "best-fit" circle, which is then divided into equal sectors, as shown in Fig. 4; the frequencies are found at each "triangle" location by applying Eq. (3).

The HP 4192 Impedance Analyzer measures the conductance and susceptance at the "triangle" frequencies, and the immittance values are stored in a file. Note the dots on the immittance loop in Fig. 4 are not exactly "equally spaced", but certainly there is a better distribution of points.
than is obtained from a linear frequency sweep. This is what we previously referred to as quasi-equally spaced points (i).

CRITICAL FREQUENCIES

Once the loop is characterized with the desired number of quasi-equally spaced points (i), specific frequency points (f) are needed for later calculations of various transducer parameters. The frequency points (f) [3] that are of interest are:

- \( f_m \) : frequency at maximum admittance (minimum impedance)
- \( f_n \) : frequency at maximum impedance (minimum admittance)
- \( f_s \) : frequency at maximum conductance
- \( f_p \) : frequency at maximum resistance
- \( f_r \) : resonance frequency (susceptance is zero)
- \( f_a \) : antiresonance frequency (susceptance is zero)
- \( f_h \) : frequency at maximum susceptance
- \( f_i \) : frequency at minimum susceptance
- \( f_{ia} \) : frequency at minimum reactance
- \( f_{ia} \) : frequency at minimum reactance

When characterizing an admittance loop, the frequency points (f) \( f_m, f_s, f_r, f_p, f_h, \) and \( f_{ia} \) are determined by a maze technique that will be described in the program section of this report. When an impedance loop is characterized, the frequency points (f) \( f_a, f_p, f_n, f_s, f_h, \) and \( f_i \) are determined. One may note that the frequency sets differ when calculating
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impedance or admittance loops. The authors believe that the two most important points (f) are the series and parallel resonance (f_s and f_p). These points (f) can easily be found, and they occur for both loaded and unloaded transducers. Both of these conditions do not apply to the frequency pairs f_m, f_n and f_a, f_r. To determine the frequencies f_m, f_n one must do a frequency sweep, which can be rather time consuming. The points (f) f_a, f_r are easy to find by implementing root-finding techniques; however, these points (f) do not always occur in loaded transducers. For these reasons, the focus has been on obtaining f_s, f_p. The reader may note that f_s is the frequency at maximum conductance; however, it is not the frequency of minimum resistance as can be seen in Fig. 5.

Analogously, f_p is the frequency at maximum resistance; but it is not the frequency of minimum conductance.

The points (f) of secondary importance are the frequencies of minimum and maximum susceptance (f_h, and f_l). These points (f), sometimes called half-power points (f), are used to compute the electrical quality factor Q. We also compute the frequencies of minimum and maximum reactance (f_h^* and f_l^*). These points (f), however, are not the half-power points (f) and cannot be used for calculating the quality factor Q. The only purpose for determining these points (f) is that they locate the frequencies at the top and bottom of the loop. The remaining frequencies are easily determined for the particular immittance loop calculated, and they serve as helpful

Fig. 5 - Impedance loop (5a) and admittance loop (5b), showing their critical frequencies.
parameters for detecting problems.

PROGRAM

The computer program MICAM, presented herein, is by no means the best implementation of the circular approximation method. However, the authors feel confident that this program can be refined in a manner that would be applicable in any research or manufacturing environment. The MICAM program, written in FORTRAN 77, is run on a Digital Equipment Corporation VAX 11/780 computer at the Underwater Sound Reference Detachment of the Naval Research Laboratory as a research tool as well as a quality-control problem detector. A version of this program is also written in HP Basic and can be executed on the HP 9836. The MICAM program has been tested on various transducers, both in air and in water, and seems to perform exceptionally well. It does have limitations, which will be explained in detail in the RESTRICTIONS section of this report. Since the program is quite involved, the line-by-line descriptions of MICAM and the program listings are included in Appendix B. The purpose of examining individual program lines is to:

- Show how the algorithm has been implemented.
- Give differences in admittance and impedance loops.
- Explain how critical frequencies are determined.

The program MICAM calls three subroutines; SIMEQ, RSORT, and FILE. The SIMEQ subroutine solves simultaneous equations. The RSORT subroutine sorts numbers in descending or ascending order. And the FILE subroutine stores the immittance information in FORTRAN files.

RESTRICTIONS

Limitations exist in all algorithms and should be used as one criteria for choosing one method over another. The following paragraphs identify two examples where a linear frequency sweep would be preferable to
determining frequencies by the circular approximation method.

One problem occurs when running very low-Q or highly damped transducers where no loops are formed. Since the circular approximation method is designed to emulate the immittance loop with a circle, the algorithm fails to converge on very low-Q or highly damped transducers. The MICAM program accommodates this problem by allowing the user to perform a frequency sweep. If the transducer is of low Q, a linear frequency sweep will give quasi-equally spaced points (i), as illustrated in Fig. 2.

A second problem occurs when two or more resonances are in the same frequency region. They may appear as small or large satellite loops. Usually the small satellite loops are not a problem and MICAM will converge to the larger loop. Nevertheless, when immittance is the combination of loops of relatively the same size, MICAM converges to one of them, depending on the initial frequency given. This loop may not necessarily be the one desired. However, the authors feel that MICAM may be optimized for specific applications by relatively minor programming changes.

CONCLUSION

The circular approximation algorithm, when used with the HP 4192A Impedance Analyzer, makes a highly efficient system for measuring impedance and admittance of resonant electromechanical devices. The system has proven to be applicable to the measurement of active electromechanical materials as well as composite transducers. The algorithm has been used with excellent results on a VAX computer as well as on personal computers.

Although specifically developed as a research tool, the automated immittance measuring system is extremely well suited for quality-control and production testing of electromechanical transducers and materials.

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REFERENCES


APPENDIX A

Analysis for Applying Equations to Both Impedance Loops

The characteristic electrical property of a piezoelectric resonator is the equivalent series chain RLC in Fig. A1. The graphical representation of the RLC branch is more easily represented by the admittance which is represented as a circle referred to as the fiducial circle [1]. The graph can be easily extended to more complicated networks connected in parallel, such as $C_0$.

![Simple equivalent circuit of a piezoelectric resonator.](image)

Fig. A1 - Simple equivalent circuit of a piezoelectric resonator.

The simple form of admittance of the RLC chain is all that is necessary to approximate the fiducial circle. The argument extends to the impedance representation in that all the information for the impedance circle is contained in the admittance circle. If

$$Y(\omega) = G(\omega) - jB(\omega),$$

then

$$\tan(\theta) = \frac{-B(\omega)}{G(\omega)}.$$  \hspace{1cm} [A1]

Since $Z(\omega)$ is the complex reciprocal of $Y(\omega)$, $Z(\omega)$ can be written as

$$Z(\omega) = \frac{G(\omega)}{G^2(\omega) + B^2(\omega)} + j\frac{B(\omega)}{G^2(\omega) + B^2(\omega)},$$  \hspace{1cm} [A2]
or \( Z(\omega) \) can be written as

\[
Z(\omega) = R(\omega) + jX(\omega). \tag{A3}
\]

Equating the real and imaginary parts of Eqs. (A2) and (A3) results in the following expressions:

\[
R(\omega) = \frac{G(\omega)}{G^2(\omega) + B^2(\omega)}, \tag{A4}
\]

and

\[
X(\omega) = \frac{B(\omega)}{G^2(\omega) + B^2(\omega)}. \tag{A5}
\]

For an impedance loop, \( \tan(\theta) \) can be written as

\[
\tan(\theta) = \frac{X(\omega)}{R(\omega)}, \tag{A6}
\]

or can be equivalently expressed by using Eqs. (A4) and (A5) as

\[
\tan(\theta) = \frac{-B(\omega)}{G(\omega)}. \]

Note that Eqs. (A1) and (A6) are identical except for being opposite in sign. Therefore for any \( \omega \) in the admittance circle there is a corresponding \( \omega \) of the same value in the impedance circle with the same but negative phase value.
APPENDIX B

Program Description and Listing

DESCRIPTION

This appendix contains a detailed description of MICAM as well as program listing. The program description supplements the CIRCULAR APPROXIMATION ALGORITHM section of this report and is necessary for a full understanding of this method. Program lines 1-76 are array declarations while lines 94-145 contain the interactive input section. There are several items of interest in this section. A question regarding speed is asked at line 98. Low speed provides an average measurement mode (approximately one measurement per second) to obtain measurement data of higher resolution and repeatability then at medium speed (5 measurements per second) or high speed (10 measurements per second). At line 112, the number of points(i) refers to the number of quasi-equally spaced points(i) that are desired on the immittance loop. In lines 118 and 120, the parallel or series resonance is required depending upon which loop is calculated. These frequencies are estimated from a priori knowledge. The more confident one is of these points(f), the smaller the frequency step size can be taken (line 125).

Lines 138-163 is a section of code that allows the user to perform a frequency sweep. This is executed only if, for some reason, the circular approximation method does not apply. The portion of code that includes lines 176-215 is the location where the conductance and susceptance (resistance and reactance) for the three initial points(f) are determined. The ARRAY variable contains the coefficients of Eq. 4. In line 216, the subroutine SIMEQ solves the three simultaneous equations, which ultimately results in the center and radius of the circle given in lines 218-220.

The code from lines 221-237 is used to solve Eq. (2) for $\omega_i$ and $1/L$, which are used to calculate the frequencies at two initial points(i) and the motional inductance value L (lines 241-250). Line 252 is a decision statement that determines if the difference between two successive series
(parallel) resonant frequencies is within a desired tolerance. If the frequency is within tolerance, the program has determined the best fit $\omega_i$ and $L$ for Eq. (1). If the tolerance is not met, a new and hopefully better-fit circle will be computed using the frequencies at the two 120-degree points (c) (lines 261-283). These 120-degree frequency points(f) are found by solving Eq. (3) and substituting the recently computed values for $\omega_i$ and $L$. This entire procedure repeats until the tolerance condition is met in line 252.

The second major computational portion of the MICAM program is found in lines 294-321. This portion uses the $\omega_i$ and $L$ that meet the tolerance specifications and Eq. (3) to calculate the quasi-equally spaced points(i). The remaining portion of the program determines the critical frequencies described earlier in this report. The RSORT subroutine sorts the data from the largest to the smallest value. In line 322, the conductance (resistance) is sorted so that the first value in the array will be the $f_s$ ($f_p$). The RSORT subroutine is called again in line 327 where frequency is the variable sorted. The remaining critical frequencies are determined by exercising a maze technique. This technique is found in lines 337-384 and is based on previous knowledge on all immittance loops, shown in Fig. 5. The criteria used are:

\[ f_m < f_s < f < f_a < f_p < f_n \]  \hspace{1cm} \text{[Bl]} 

A critical frequency point(f) is searched only in the region wherein it could occur; i.e., it satisfies the inequalities of Eq. (Bl). All of the critical frequencies are chosen from the points(i&f) of the immittance loop except for $f_p$ ($f_s$). The points(f) $f_p$ ($f_s$) require that more points(f) be calculated in order to have relatively accurate data. For example, when an admittance loop has been run, $f_p$ is determined by switching the HP analyzer to the impedance mode, spotting the point(f) $f_{1a}$, and sweeping the frequency until the frequency at maximum impedance is found. On the other hand, when an impedance loop has been run, $f_s$ is determined by switching the analyzer to the admittance mode, spotting the point(f) $f_{1a}$, and then sweeping the frequency in reverse until the frequency of maximum admittance is found. This technique is illustrated in lines 408-431.
The remaining portion of the program can be considered a formatted output section that prints a table of all critical frequencies described and files the data points for plotting. The plots that can be created include a graph of magnitude of immittance versus frequency and a graph of the imaginary part of immittance versus the real part of immittance. Also the critical frequencies are stored so they may be overlayed on the immittance plot as shown in Figs. B1 and B2, which are examples of admittance loops obtained on a USRD Type F42A transducer in air and in the USRD Lake Facility by MICAM.

There are several differences in MICAM for impedance or admittance loops. The first difference, of course, is that the HP analyzer is in the proper mode for the desired measurements (lines 171 and 172). Secondly, there is a difference in the motional resistance (R) found in Eqs. (1) through (3) for the two loops. In the admittance mode, R is approximated by the reciprocal of the diameter, and in the impedance mode, R is approximated by simply using the diameter of the circle. Two interactive runs of the program MICAM are included in Appendix B, which illustrate how...
the user can obtain results in either immittance mode.
LISTING

0001
0002
0003  C  MICAM PROGRAM
0004
0005  C  WRITTEN BY TINA RUGGIERO
0006  C  FEBRUARY, 1983
0007
0008  C  THIS PROGRAM DETERMINES A FREQUENCY SWEEPING FUNCTION BY APPROXimating
0009  C  AN ADMITTANCE LOOP WITH A PERFECT CIRCLE. ALSO FN, FM,
0010  C  FA, FR, AND ADMITTANCE LOOPS ARE STORED AND ARE AVAILABLE
0011  C  FOR PLOTTING.
0012
0013
0014  DOUBLE PRECISION DEF (3), CONS (3), ARRAY (3, 3), COEFF (3, 3), COLUMN (3), ANS (3)
0015  REAL RES (1000), XES (1000), FREQ (1000), X (6), Y (6), F (6), FR (3), FRE (1000)
0016  REAL K33, CE, CP, COB, CAP, XCOF (5), COF (5), ROOR (5), ROOT (5), ADM (1000)
0017  REAL CRX (8), CRY (9), MAG (1000)
0018  COMMON FR, AMR, RR, XR, FA, AM, RA, XA, FM, AMM, RM, XM, FN, AMN, RN, XN, XH, XL
0019  COMMON RH, RL, FH, FL
0020  COMMON /LENGTH/ LEN
0021
0022
0023  BYTE ANSWER (80)
0024
0025  BYTE A (13)
0026  DATA A /'O', 'L', 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 'E', 'N'/
0027
0028  BYTE B (12)
0029  DATA B /'T', 'F', 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 'E', 'N'/
0030
0031  BYTE C (13)
0032  DATA C /'P', 'F', 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 'E', 'N'/
0033
0034  BYTE D (12)
0035  DATA D /'S', 'F', 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 'E', 'N'/
0036
0037  BYTE E (13)
0038  DATA E /'P', 'R', 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 'E', 'N'/
0039  BYTE IDSP (4)
0040  DATA IDSP /'F', 'I', 'A', '4'/
0041
0042  BYTE IADV (2)
0043  DATA IADV /'W', '2'/
0044
0045  BYTE IREV (2)
0046  DATA IREV /'W', '4'/
0047
0048  BYTE IAD1 (2)
0049  DATA IAD1 /'D', '1'/
0050
0051  BYTE IADO (2)
DATA IADO '/D', '0'/
BYTE IADM(4)
DATA IADM/'F', '1', 'A', '2'/
BYTE IAV1(2)
DATA IAV1/'Y', '1'/
BYTE IA1(2)
DATA IAH1/'H', '1'/
BYTE IA0(2)
DATA IAH0/'H', '0'/
BYTE IAMM(2)
DATA IAMM/'W', '0'/
BYTE IAC3(2)
DATA IAC3/'C', '3'/
BYTE IAC2(2)
DATA IAC2/'C', '2'/
BYTE IAEX(2)
DATA IAEX/'E', 'X'/
IADDR=1
ITIMO=30
LUN=1
CALL BTAKEC(LUN, ISTAT)
CALL BDEVCL (IADDR, ISTAT)
AMM= 10000.
LENGTH1=35
LENGTH2=21
LENGTH3=80
1053 FORMAT(F9.5)
AMN=0.
WRITE(5, 888)
FORMAT(’99 DO YOU WANT 1)IMPE DANCE 2)ADMITTANCE ’)
READ(5, 889) ILOOP
FORMAT(I2)
WRITE(5, 900)
FORMAT(’999 DO YOU WANT 1)LOW, 2)MED. 3)HIGH SPEED ’)
READ(5, 950) IAVE
FORMAT(I2)
WRITE(5, 1000)
FORMAT(/"$, 'ENTER THE VOLTAGE LEVEL (IN VOLTS): "')
READ(5, 1060, ERR=10) VOLTS
ENCODER(9, 1070, A(3)) VOLTS
CALL BWRITE(IADDR, A, 13, ISTAT)
FORMAT(F10.0)
FORMAT(F9.4)
NTIMES=1
WRITE(5, 1111)
FORMAT(/"$, 'ENTER # OF POINTS ') READ(5, 1020) NPTS
FORMAT(I4)
NTIMES=NTIMES+1
IF (ILOOP .EQ. 1) WRITE(5, 1010)
FORMAT(/"$, 'ENTER FREQUENCY (PARALLEL RESONANCE) (IN KHZ): ') IF (ILOOP .EQ. 2) WRITE(5, 1011)
FORMAT(/"$, 'ENTER FREQUENCY (SERIES RESONANCE) (IN KHZ): ') READ(5, 1060, ERR=20) START_FREQ
ITIME=1
WRITE (5, 1030)
FORMAT('CENTER STEP FREQ (IN KHZ): ') READ(5, 1060) STEP_FREQ
IF(NTIMES .LT. 5) THEN
GOTO 3000
ELSE
TYPE *, 'DO YOU WANT TO SWEEP FREQ'
READ (5, 1035) ISWEEP
FORMAT(A2)
IF (ISWEEP .EQ. 'N') THEN
NTIMES=-10
GO TO 3000
END IF
I=1
ENCODER(8, 1066, D(3)) STEP_FREQ
CALL BWRITE(IADDR, D, 12, ISTAT)
WRITE(5, 1040)
FORMAT(/"$, 'ENTER THE STOPPING FREQ (KHZ) ') READ(5, 1060) STOP
ENCODER(9, 1070, C(3)) STOP
ENCODER(9, 1070, E(3)) START_FREQ
CALL BWRITE(IADDR, E, 13, ISTAT)
CALL BWRITE(IADDR, IAMM, 2, ISTAT)
CALL BWRITE(IADDR, IAEX, 2, ISTAT)
DO J=1, 80
ANSWER(J)=0
END
0154 END DO
0155 CALL BREAD(IADDR, ANSWER, LENGTH3, ISTAT)
0156 DECODE(12, 1050, ANSWER(5)) RES(I)
0157 DECODE(12, 1050, ANSWER(21)) XES(I)
0158 DECODE(9, 1053, ANSWER(35)) FREQ(I)
0159 IF (FREQ(I) .GE. STOP) GOTO 88
0160 CALL BWRITE(IADDR, IADV, 2, ISTAT) IADVANCE FREQ.
0161 I=I+1
0162 GO TO 1044
0163 END IF
0164 3000 STEPI=STEP_FREQ
0165 IF (IAVE .EQ. 1) CALL BWRITE(IADDR, IAV1, 2, ISTAT) IAVERAGE SPEED
0166 IF (IAVE .EQ. 3) CALL BWRITE(IADDR, IAH1, 2, ISTAT) IHIGH SPEED
0167 IF (IAVE .EQ. 2) CALL BWRITE(IADDR, IAH0, 2, ISTAT) INORMAL SPEED
0168 CALL BWRITE(IADDR, IAMM, 2, ISTAT) IMANUAL MODE
0169 IF (LOOP .EQ. 2) CALL BWRITE(IADDR, IAT3, 2, ISTAT) ICIRCUIT TYPE 3
0170 IF (LOOP .EQ. 1) CALL BWRITE(IADDR, IAT2, 2, ISTAT) ICIRCUIT TYPE 2
0171 48 IF (IT .GT. 1) CONTINUE
0172 49 DO I=1,3
0173 IF (ITIME .GE. 2) THEN
0174 IF (I .EQ. 2) GOTO 85
0175 FREQUENCY=ABS(FR(I)/(1000.*2*3.14159))
0176 ENCODE(9,1070, E(3)) FREQUENCY
0177 CALL BWRITE(IADDR, E, 13, ISTAT)
0178 FREQ(I)=FREQUENCY
0179 ELSE
0180 ENCODE(9,1070, E(3)) START_FREQ I SPOT STARTING POINT
0181 CALL BWRITE(IADDR, E, 13, ISTAT)
0182 FREQ(I)=START_FREQ
0183 END IF
0184 CALL BWRITE(IADDR, IAE, 2, ISTAT) ITIGGER THE READING
0185 DO J=1,80
0186 ANSWER(J)=0
0187 END DO
0188 K=0
0189 CALL BREAD(IADDR, ANSWER, LENGTH1, ISTAT)
0190 DECODE(12, 1050, ANSWER(5)) RES(I)
0191 DECODE(12, 1050, ANSWER(21)) XES(I)
0192 1050 FORMAT(E12.2)
0193 IF (ITIME .EQ. 1 .AND. I .EQ. 1) THEN
0194 FREQA=FREQ(I)
0195 XESA=XES(I)
0196 RESA=RES(I)
0197 ELSE
0198 END IF
0199 FREQA=FREQ(I)*1000
ARRAY(I,1)=RES(I)
ARRAY(I,2)=XES(I)
ARRAY(I,3)=1.
CONS(I)=-(RES(I)*RES(I)+XES(I)*XES(I))
IF (ITIME.EQ.1)START_FREQ=START_FREQ+STEP_FREQ
END DO

C SIMEQ IS A SUBROUTINE THAT SOLVES SIMULTANEOUS EQUATIONS
C USED TO FIND COEFFICIENTS OF A GENERALIZED CIRCLE

N=3
CALL SIMEQ(N,ARRAY,CONS,DEF)
IF(N.EQ.0)GO TO 20
CENTERX=-DEF(1)/2.
CENTERY=-DEF(2)/2.
RADIUS=.5*SQRT(DEF(1)*DEF(1)+DEF(2)*DEF(2)-4*DEF(3))
IF(LOOP.EQ.2)RESIS=1./(2*RADIUS)
RESISTANCE (ADMITTANCE)
IF(LOOP.EQ.1)RESIS=2*RADIUS
RESISTANCE (IMPEDANCE)
C SLOPE IS THE TAN(THETA) IN EQUATION 1
SLOPE1=((XES(1)-CENTERY)/(RES(1)-CENTERX+RADIUS))
SLOPE2=((XES(2)-CENTERY)/(RES(2)-CENTERX+RADIUS))
SLOPE3=((XES(3)-CENTERY)/(RES(3)-CENTERX+RADIUS))
COEFF(1,1)=SLOPE1*RESIS*6.283185*FREQ(1)
COEFF(2,1)=SLOPE2*RESIS*6.283185*FREQ(2)
COEFF(1,2)=1.
COEFF(2,2)=1.
COLUMN(1)=(2*3.14159*FREQ(1))**2
COLUMN(2)=(2*3.14159*FREQ(2))**2
N=2
CALL SIMEQ(N,COEFF,COLUMN,ANS)
IF(N.EQ.0)GO TO 20
C ANS(I) is the Inductor
C ANS(2) is the Resonant Freq.
IF(ANS(2).LT.0)GOTO 20
ANS(1)=1./ANS(1)
ANS(2)=SQRT(ANS(2))
RESONANCE=ANS(2)/6283.185
WRITE(5,77)ANS(2)/6283.185
77 FORMAT('FREQ= ',F10.3)
IF(ABS(ANS(2)-OMEGA)/6283.185.LE.(.0005*FREQA) .OR. ITIME.GE. 25)THEN
ANS(2)=(OMEGA+ANS(2))/2.
ANS(1)=(RINDUCT0R+ANS(1))/2.
GOTO 50
ELSE
ENDIF
ELSE
OMEGA=ANS(2)
RINDUCTOR=ANS(1)
END IF

C ANGLES OF OTHER 2 POINTS

TRANSX1=RES(2)−CENTERX
TRANSY1=XES(2)−CENTERY
TRANS1=ATAN2(TRANSY1, TRANSX1)

X2=COS(TRANS1+2.094395)*RADIUS+CENTERX
X3=COS(TRANS1−2.094395)*RADIUS+CENTERX
Y2=SIN(TRANS1+2.094395)*RADIUS+CENTERY
Y3=SIN(TRANS1−2.094395)*RADIUS+CENTERY

SLOPE1=(Y2−CENTERY) / (X2−CENTERX+RADIUS)
SLOPE3=(Y3−CENTERY) / (X3−CENTERX+RADIUS)

B1=−SLOPE1*RESIS
B2=−SLOPE2*RESIS
B3=−SLOPE3*RESIS

FR(1)=−B1−SQRT(B1*B1+4.*ANS(1)**2*(ANS(2)*ANS(2)))
FR(1)=FR(1) / (2*ANS(D)
FR(2)=FREQ(2) *2*3.14159
FR(3)=−B3−SQRT(B3*B3+4.*ANS(1)**2*(ANS(2)*ANS(2)))
FR(3)=FR(3) / (2*ANS(1))

ITIME=ITIME+1
IF (ITIME .GE. 2) GOTO 49

R=SQRT(RESA*RESA+XESA*XESA)
THETA=ATAN2(XESA, RESA)
A0=SQRT((CENTERX−RESA)**2 + (CENTERY−XESA)**2)
CONVERT=1.74532E−02
TIM=359. /NPTS
PI=3. 14159

TRANSX=RESA−CENTERX
TRANSY=XESA−CENTERY
THETA=ATAN2(TRANSY, TRANSX)

I=1
DO IT=1, NPTS
DELTA2=IT*TIM*CONVERT+THETA
X3=(COS(DELTA2) *RADIUS)+CENTERX
Y3=(SIN(DELTA2) *RADIUS)+CENTERY
SLOPE3=(Y3−CENTERY) / (X3−CENTERX+RADIUS)

B3=−SLOPE3*RESIS

FRE(I)=−B3−SQRT(B3*B3+4.*ANS(1)**2*(ANS(2)*ANS(2)))
FRE(I)=FRE(I) / (2.*ANS(1))
FREQUENCY=ABS(FRE(I) / (1000. *2*3.14159))
TOLERANCE1=2.5*RESONANCE
IF (FREQUENCY .GT. TOLERANCE1) GOTO 70
ENCODE(9, 1070, E(3)) FREQUENCY I SPOT STARTING POINT

CALL BWRITE(IADDR, E, 13, ISTAT)

CALL BWRITE(IADDR, IAEX, 2, ISTAT) ITRIGGER THE READING

DO J=1, 80
   ANSWER(J) = 0
   K = 0
   CALL BREAD(IADDR, ANSWER, LENGTH1, ISTAT)
   DECODE(12, 1050, ANSWER(5)) RES(I)
   DECODE(12, 1050, ANSWER(21)) XES(I)
   IF RES(I) GT 1.3E6 OR XES(IT) GT 1.3E6 GO TO 70
   FREQ(I) = FREQUENCY
   MAG(I) = SQRT(RES(I) * RES(I) + XES(I) * XES(I))
   I = I + 1
   70 END DO

K = 0
   CALL BREAD(IADDR, ANSWER, LENGTH1, ISTAT)
   DECODE(12, 1050, ANSWER(5)) RES(I)
   DECODE(12, 1050, ANSWER(21)) XES(I)
   IF RES(I) GT 1.3E6 OR XES(IT) GT 1.3E6 GO TO 70
   FREQ(I) = FREQUENCY
   MAG(I) = SQRT(RES(I) * RES(I) + XES(I) * XES(I))
   I = I + 1
   70 END DO

CALL RSORT(FREQ, RES, XES, I-1, 1)

GS = RES(1)
BS = XES(1)
FS = FREQ(1)

TAN0 = ATAN2(BS, GS)

CALL RSORT(FREQ, RES, XES, I-1, 1)

FLAG = 0

DO J = 2, I-1
   IF XES(J) GT BS .AND. FLAG .EQ. 0 .AND. XES(J) .GT. 0) THEN
      FREQ(1) = FREQ(J)
      RES(1) = RES(J)
      XES(1) = XES(J)
      GO TO 500
   ELSE
      FREQ(IT) = FREQ(J)
      RES(IT) = RES(J)
      XES(IT) = XES(J)
      TAN1 = ATAN2(XES(IT), RES(IT))
      FLAG = 1
      ADM(IT) = SQRT(RES(IT)**2 + XES(IT)**2)
      IF (FREQ(IT) .LE. FS AND IT .GT. 1) THEN
         IF XES(IT) .GE. XESMAX THEN
            XESMAX = XES(IT)
            FH = FREQ(IT)
            GH = RES(IT)
            BH = XES(IT)
            END IF
         IF (ADM(IT) .GT. ADMMAX .AND. ILOOP .EQ. 2) THEN

         25
ADMMAX=ADM(IT)
FM=FREQ(IT)
GM=RES(IT)
BM=XES(IT)
END IF
IF(XES(IT-1) .LT. 0 .AND. XES(IT) .GT. 0)THEN
FRES=FREQ(IT)
GR=RES(IT)
BR=XES(IT)
END IF
END IF
IF(FREQ(IT) .GE. FS .AND. IT .GT. D)THEN
IF(XES(IT) .LE. XESMIN)THEN
XESMIN=XES(IT)
FL=FREQ(IT)
GL=RES(IT)
BL=XES(IT)
END IF
IF(XES(IT-1) .LT. 0 .AND. XES(IT) .GT. 0)THEN
FRES=FREQ(IT)
GR=RES(IT)
BR=XES(IT)
END IF
IF(ADM(IT) .GT. ADMMAX .AND. ILOOP .EQ. D)THEN
ADMMAX=ADM(IT)
FN=FREQ(IT)
GN=RES(IT)
ENDIF
END IF
IT=IT+1
END IF
END DO
IF(ILOOP .EQ. D)THEN
WRITE (5,1109)
1109 FORMAT(/,9X,'TYPE',11X,'FREQUENCY (KHZ)',2X,'RESISTANCE',2X,'REACTANCE')
ELSE
WRITE (5,1110)
1110 FORMAT(/,9X,'TYPE',11X,'FREQUENCY (KHZ)',2X,'CONDUCTANCE',2X,'SUSCEPTANCE')
END IF
WRITE (5,1112)
1112 FORMAT(9X,'--',11X,'--------',2X,'------',
12X,'--------',/)
IF(FRES .EQ. 0)THEN
IF(BL .LT. 0)THEN
FRES=FS
GR=GS
BR=BS
WRITE(5,1130)FRES,GR,BR
0409    ELSE
0410    WRITE(5, 1120)
0411 1120 FORMAT(1X,'RESONANCE', 17X, 'DOES NOT EXIST')
0412    END IF
0413 ELSE
0414    IF (ILOOP .EQ. 2) WRITE (5, 1130) FRES, GR, BR
0415 1130 FORMAT (1X,'RESONANCE', 16X, F8.3, 7X, E8.3, 5X, E9.3)
0416    IF (ILOOP .EQ. 1) WRITE (5, 1131) FRES, GR, BR
0418 END IF
0419    CALL BWRITE (IADDR, IAMM, 2, ISTAT)
0420    FLAG = 1
0421    ENCODE (D, 1066, D(3)) . 1
0422    CALL BWRITE (IADDR, D, 12, ISTAT)
0423    IF (ILOOP .EQ. 1) CALL BWRITE (IADDR, IAC3, 2, ISTAT)
0424    IF (ILOOP .EQ. 2) CALL BWRITE (IADDR, IAC2, 2, ISTAT)
0425    IF (ILOOP .EQ. 2) ENCODE (9, 1070, E(3)) FL
0426    IF (ILOOP .EQ. 1) ENCODE (9, 1070, E(3)) FH
0427    CALL BWRITE (IADDR, E, 13, ISTAT)
0428    GP = 0
0429 1270 CALL BWRITE (IADDR, IAEX, 2, ISTAT)
0430    DO J = 1, 80
0431    ANSWER(J) = 0
0432    END DO
0433    CALL BREAD (IADDR, ANSWER, LENGTH3, ISTAT)
0434    DECODE (12, 1050, ANSWER(5)) A1
0435    DECODE (12, 1050, ANSWER(21)) A2
0436    DECODE (9, 1053, ANSWER(35)) F1
0437    IF (A1 .GE. GP) THEN
0438    FP = F1
0439    GP = A1
0440    BP = B1
0441    IF (ILOOP .EQ. 2) CALL BWRITE (IADDR, IADV, 2, ISTAT)
0442    IF (ILOOP .EQ. 1) CALL BWRITE (IADDR, IREV, 2, ISTAT)
0443    GO TO 1270
0444 ELSE
0445    FLAG = FLAG + 1
0446    IF (FLAG .EQ. 1) THEN
0447    IF (ILOOP .EQ. 2) CALL BWRITE (IADDR, IADV, 2, ISTAT)
0448    IF (ILOOP .EQ. 1) CALL BWRITE (IADDR, IREV, 2, ISTAT)
0449    FP = F1
0450    GP = A1
0451    BP = B1
0452    GO TO 1270
0453 END IF
0454 END IF
0455    NUM = 8
0456    CRX(1) = GS
0457    CRY(1) = BS
0458    CRX(2) = GP
0459    CRY(2) = BP
RUGGIERO AND HENRIQUEZ

0460  CRX(3)=GM
0461  CRY(3)=BM
0462  CRX(4)=GN
0463  CRY(4)=BN
0464  CRX(5)=GH
0465  CRY(5)=BH
0466  CRX(6)=GL
0467  CRY(6)=BL
0468  IF(FRES .EQ. 0) THEN
0469      NUM=NUM+1
0470  ELSE
0471      CRX(7)=GR
0472      CRY(7)=BR
0473  END IF
0474  IF(FA .EQ. 0) THEN
0475      NUM=NUM+1
0476  ELSE
0477      CRX(8)=GA
0478      CRY(8)=BA
0479  END IF
0480  IF(ILOOP .EQ. 2) WRITE (5, 1160) FS, GS, BS
0481  IF(ILOOP .EQ. 1) WRITE (5, 1170) FP, GP, BP
0482  1160  FORMAT (1X, 'SERIES RESONANCE', 9X, F8.3, 7X, E8.3, 5X, E9.3)
0483  IF(ILOOP .EQ. 2) WRITE (5, 1180) FM, GM, BM
0484  IF(ILOOP .EQ. 1) WRITE (5, 1190) FN, GN, BN
0486  IF(ILOOP .EQ. 2) WRITE (5, 1200) FL, GL, BL
0487  IF(ILOOP .EQ. 1) WRITE (5, 1210) FS, GS, BS
0488  1180  FORMAT (1X, 'MAXIMUM ADMITTANCE', 7X, F8.3, 7X, E8.3, 5X, E9.3)
0489  1190  FORMAT (1X, 'MAXIMUM IMPEDANCE', 8X, F8.3, 7X, E8.3, 5X, E9.3)
0490  1280  WRITE (5, 1200) FL, GL, BL
0491  1290  WRITE (5, 1210) FS, GS, BS
0493  1210  WRITE (5, 1300) FS, GS, BS
0494  1300  WRITE (5, 1310) FS, GS, BS
0495  1301  TYPE ('/A1')
0496  IF(ILOOP .EQ. 2) TYPE '*','ADMITTANCE LOOP'
0497  IF(ILOOP .EQ. 1) TYPE '*','IMPEDANCE LOOP'
0498  CALL FILE (IT-1, RES, XES)
0499  TYPE '*','
0500  TYPE '*','CRITICAL FREQUENCIES'
0501  CALL FILE (NUM, CRX, CRY)
0502  TYPE '*','
0503  TYPE '*','FREQ VS. MAG.'
0504  CALL FILE (IT-1, FREQ, MAG)
0505  CALL BDEVC'L (IADDR, ISTAT)
0506  CLEAR SELECTED
0507  END
APPENDIX C

Running MICAM

RUN SUPER
DO YOU WANT 1) IMPEDANCE 2) ADMITTANCE 1
DO YOU WANT 1) LOW, 2) MED, 3) HIGH SPEED 3

ENTER THE VOLTAGE LEVEL (IN VOLTS): .1
ENTER # OF POINTS 100

ENTER FREQUENCY (PARALLEL RESONANCE) (IN KHZ): 15
ENTER STEP FREQ (IN KHZ): .5
FREQ= 15.304
FREQ= 15.293
FREQ= 15.291

<table>
<thead>
<tr>
<th>TYPE</th>
<th>FREQUENCY(KHZ)</th>
<th>RESISTANCE</th>
<th>REACTANCE</th>
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<tr>
<td>ANTIRESONANCE</td>
<td>15.291</td>
<td>.107E+07</td>
<td>0.100E+05</td>
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<tr>
<td>SERIES RESONANCE</td>
<td>14.384</td>
<td>.495E-02</td>
<td>-.288E-02</td>
</tr>
<tr>
<td>PARALLEL RESONANCE</td>
<td>15.291</td>
<td>.107E+07</td>
<td>0.100E+05</td>
</tr>
<tr>
<td>MAXIMUM IMPEDANCE</td>
<td>15.291</td>
<td>.107E+07</td>
<td>0.100E+05</td>
</tr>
<tr>
<td>HIGH POINT</td>
<td>15.284</td>
<td>.530E+06</td>
<td>0.530E+06</td>
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<tr>
<td>LOW POINT</td>
<td>15.297</td>
<td>.630E+06</td>
<td>-.540E+06</td>
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</tbody>
</table>

IMPEDEANCE LOOP
FILE NAME FOR X,Y DATA: DATA1

CRITICAL FREQUENCIES
FILE NAME FOR X,Y DATA: DATA2

FREQ VS. MAG.
FILE NAME FOR X,Y DATA: DATA3
RUN SUPER
DO YOU WANT 1) IMPEDANCE 2) ADMITTANCE 2
DO YOU WANT 1) LOW, 2) MED, 3) HIGH SPEED 3

ENTER THE VOLTAGE LEVEL (IN VOLTS): .1
ENTER # OF POINTS 100

ENTER FREQUENCY(SERIES RESONANCE) (IN KZH): 14
ENTER STEP FREQ (IN KHZ): .5
FREQ= 14.390
FREQ= 14.372
FREQ= 14.372

<table>
<thead>
<tr>
<th>TYPE</th>
<th>FREQUENCY(KHZ)</th>
<th>CONDUCTANCE</th>
<th>SUSCEPTANCE</th>
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<tr>
<td>RESONANCE</td>
<td>14.375</td>
<td>.678E-02</td>
<td>0.300E-04</td>
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<td>SERIES RESONANCE</td>
<td>14.373</td>
<td>.679E-02</td>
<td>0.540E-03</td>
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<tr>
<td>PARALLEL RESONANCE</td>
<td>15.291</td>
<td>.107E+07</td>
<td>0.000E+00</td>
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<tr>
<td>MAXIMUM ADMITTANCE</td>
<td>14.373</td>
<td>.677E-02</td>
<td>0.790E-03</td>
</tr>
<tr>
<td>HIGH POINT</td>
<td>14.357</td>
<td>.311E-02</td>
<td>0.379E-02</td>
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<tr>
<td>LOW POINT</td>
<td>14.391</td>
<td>.327E-02</td>
<td>-.316E-02</td>
</tr>
</tbody>
</table>

ADMITTANCE LOOP
FILE NAME FOR X,Y DATA: DATA1

CRITICAL FREQUENCIES
FILE NAME FOR X,Y DATA: DATA2

FREQ VS. MAG.
FILE NAME FOR X,Y DATA: DATA3
$