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Analysis and Computerized Design of NMR Probe Circuits

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ABSTRACT

A procedure for designing four different NMR probe circuits is described. Equations are derived which allow accurate estimates for tuning components. Graphs of theoretical frequency responses are presented. An accurate method for measuring effective quality factors, Q_{eff}, is described. Four probe circuits are constructed and evaluated with respect to power efficiency, ringdown time and signal/noise. Finally, A FORTRAN computer program which will implement the design procedures described in this report is presented.

I. Introduction

A knowledge of the circuits used to design NMR probes is not only useful but also very advantageous to the experimentalist. This report presents a general approach to understanding and predicting the behavior of four standard RF matching circuits which can be used to design NMR probes. For each of these circuits mathematical equations are derived which allow tuning elements (capacitors and/or cable lengths) to be calculated, and frequency responses to be predicted.

Equations are derived which allow the effective Q of the NMR probe to be estimated from a specific component value measured after the probe is assembled and tuned. Design graphs which allow fast estimates of component values are also presented.

An experimental comparison of the four circuits under very similar conditions is described. The evaluations of the performance of each circuit are made by comparing power efficiencies (as measured by pulse widths required to rotate a magnetic moment by 90.0°), ringdown times (as measured by the time required for receiver noise to predominate following a strong RF pulse) and signal/noise ratios.

Included in this report is a FORTRAN computer program which was used to make the numerical calculations and draw the frequency response and design graphs.

This report will not discuss the criteria for choosing a given coil, probe box layout, components and the like. These have been well discussed in the literature.

II. Theory and Equations of the Four NMR Probe Circuits

Useful solutions of the standard circuit equations of four RF matching circuits will be derived. The circuits are named: tapped parallel tuned circuit, tapped series tuned circuit ("Tapped" refers to the fact that the impedances of simple parallel and series resonant circuits are tapped at an impedance, $Z_{IN} = Z_o$ at phase angle, $\phi_{IN} = 0.0°$.), hybrid tuned circuit ("Hybrid" refers to the fact that a tuning element with a transcendental frequency response, namely a cable, is used.) and finally the shorted stub tuned circuit (A stub is a small length of cable used as a tuning element). All circuits allow a load which is composed of an inductor L, with inductive reactance, X_L, and a series resistor, R_L, to be matched to the characteristic impedance of the cable (transmission line) feeding the probe. This condition can be expressed as: $Z_{IN} = Z_o$ and $\phi_{IN} = 0.0°$ at a resonant frequency, f_o. The complex number, $(Z_{IN}, < \phi_{IN})$ is the input impedance looking into the probe and Z_o is the characteristic impedance (or resistance) of the cable feeding the probe. Both of these numbers are assumed real and therefore represent resistances.

All reactive elements (inductors and capacitors) and all cables are considered ideal and lossless. All ohmic losses are considered lumped into an equivalent resistance, R_L, in series with the NMR coil. The effective value of R_L can be calculated after the probe is constructed and tuned as will be shown below.

In all derivations the following definitions apply:

$$X_{C1} = (2\pi f_o \; C_{C1})^{-1} \tag{1}$$

$$X_{C2} = (2\pi f_o \; C_{C2})^{-1} \tag{2}$$

$$X_L = Z_L (\sin \phi_L) = 2\pi f_o L \tag{3}$$

$$R_L = Z_L (\cos \phi_L) \tag{4}$$

$$Z_L = \sqrt{R_L^2 + X_L^2} \tag{5}$$

$$Q = {}^{X}L/R_L = \tan \phi_L \tag{6}$$

X_{C1} and X_{C2} are the capacitive reactances of capacitors C_{C1} and C_{C2} at frequency, f_o. X_L is the inductive reactance of the entire load which consists of inductor, L, and series resistor, R_L. R_L is the resistance of the entire load. Q is the quality factor of the load. Q is a measure of a circuits ability to store energy. Both Z_{IN} and $Y_{IN} = {}^1/Z_{IN}$, either represent complex quantities or, when a phase angle is present, just the magnitude of the complex number. In the laboratory, quantities such as Z_{IN} and Z_o would be read on a vector impedance meter. The equations used to calculate component values and theoretical or "ideal" frequency response are derived using the standard theory of linear circuit analysis.[1]

IIA. The Tapped Parallel-Tuned Circuit

The circuit diagram is shown in Figure 1. Capacitors C_{C1} and C_{C2}

TAPPED PARALLEL TUNED CIRCUIT

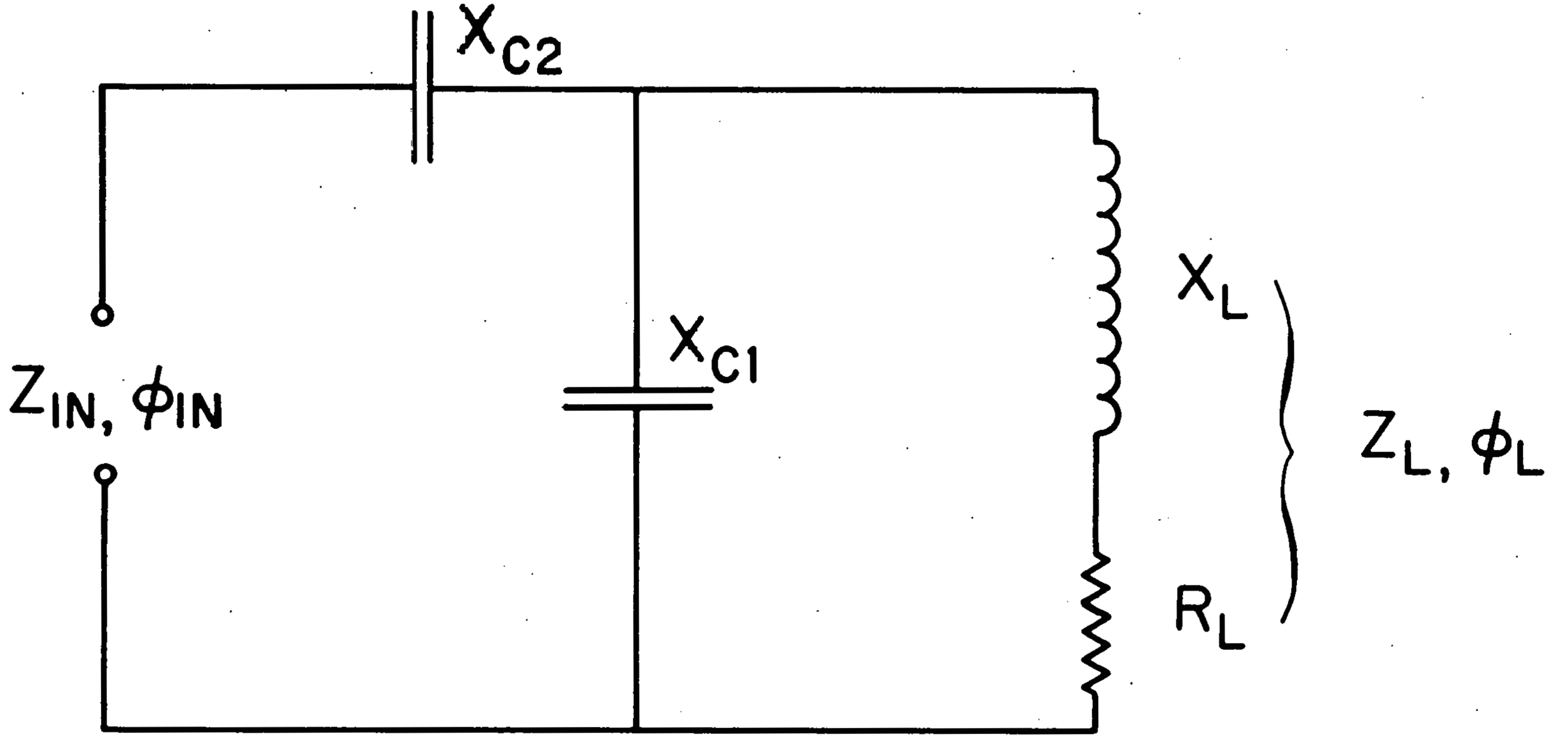


Fig. 1. Circuit diagram of the tapped parallel tuned circuit. A load, inductive reactance X_L and resistance R_L, is tuned to input impedance (Z_{IN}, ϕ_{IN}) at frequency f_o by capacitive reactances X_{C1} and X_{C2}.

are used to tune a load, X_L and R_L, to an input impedance $Z_{IN} = Z_o$, $\phi_{IN} = 0.0°$ at frequency f_o.

Using standard linear circuit analysis, the input impedance, Z_{IN}, can be shown to be:

$$Z_{IN} = -jX_{C2} + \frac{X_{C1}X_L - j\,X_{C1}\,R_L}{R_L + j\,(X_L - X_{C1})} \tag{7}$$

The conditions:

$\text{Real}\,(Z_{IN}) = Z_o$

$\text{Imaginary}\,(Z_{IN}) = 0.0$

will result in $Z_{IN} = Z_o$, $\phi_{IN} = 0.0°$ at f_o. With these conditions it can be shown that

$$C_{C1} = \left[\frac{2\pi f_o \;(Z_oX_L + \sqrt{Z_oR_L \;\;(R_L^2 + X_L^2 - Z_o R_L)}}{Z_o - R_L} \right]^{-1} \tag{8}$$

$$X_{C1} = (\,2\pi f_o\, C_{C1})^{-1}$$

$$C_{C2} = C_{C1} \left[\frac{R_L^2 + (X_{C1} - X_L)^2}{(X_{C1} - X_L)\,X_L - R_L^2} \right] \tag{9}$$

Usually the condition

$Q >> \dfrac{X_L\,Z_o}{X_{C1}^2}$ is a valid approximation for most NMR probe circuits. The solutions then reduce to:

$$C_{C1} = \left[\frac{2\pi f_o\, X_L\,(Z_o + \sqrt{Z_oR_L})}{Z_o - R_L} \right]^{-1} \tag{9a}$$

$$A = \frac{X_L\,(1 + \sqrt{Z_o/R_L}\,)}{Z_o - R_L}\ , \quad Q = \frac{X_L}{R_L}$$

$$C_{C2} = C_{C1}\left(\frac{1 + A^2}{AQ - 1}\right). \tag{9b}$$

Furthermore, usually both

A^2 and $AQ >> 1$

thon:

$$C_{C2} = \left[\frac{2\pi f_o\ X_L\,(Z_o + \sqrt{Z_o R_L})}{R_L + \sqrt{Z_o R_L}}\right]^{-1} \tag{9c}$$

IIB. The Tapped Series - Tuned Circuit

The circuit diagram is shown in Figure 2. Capacitors C_{C1} and C_{C2} are used to tune a load, X_L and R_L, to an input impedance $Z_{IN} = Z_o$, $\phi_{IN} = 0.0°$ at frequency f_o.

Using standard linear circuit analysis, the input admittance, Y_{IN}, can be shown to be;

$$Y_{IN} = {}^{j}/X_{C2} + \frac{1}{R_L + j\,(X_L - X_{C1})} \tag{10}$$

The conditions:

Real $(Y_{IN}) = 1/Z_o$

Imaginary $(Y_{IN}) = 0.0$

will result in $Z_{IN} = 1/Y_{IN} = Z_o$, $\phi_{IN} = 0.0°$ at f_o. With these conditions it can be shown that

$$C_{C1} = \left[2\pi f_o\,(X_L - R_L\sqrt{\frac{Z_o}{R_L} - 1}\,)\right]^{-1} \tag{11}$$

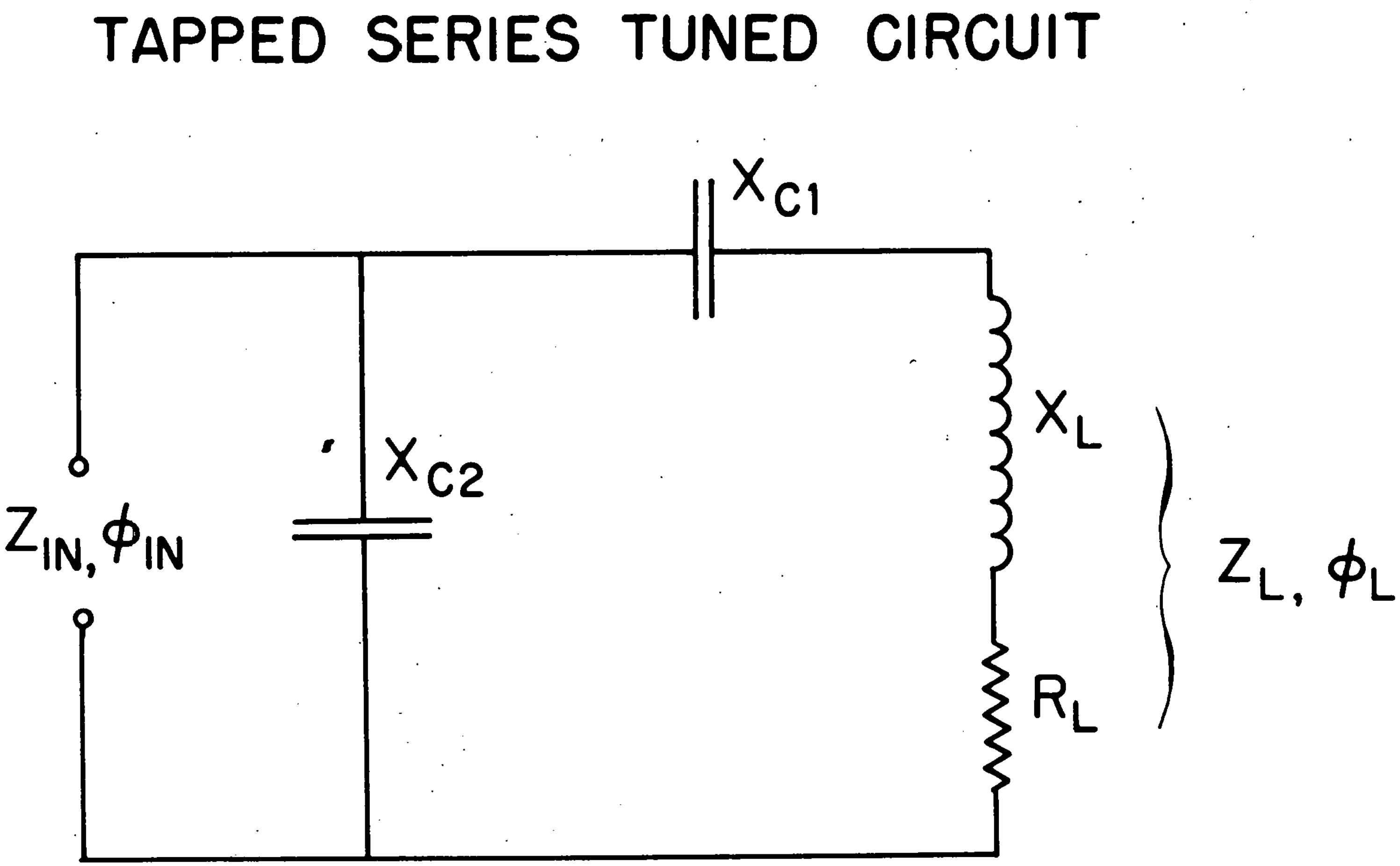


Fig. 2. Circuit diagram of the tapped series tuned circuit. A load, inductive reactance X_L and resistance R_L, is tuned to input impedance (Z_{IN}, ϕ_{IN}) at frequency f_o by capacitive reactances X_{C1} and X_{C2}.

$$C_{C2} = \frac{\sqrt{\frac{Z_o}{R_L} - 1}}{2\pi f_o Z_o} \qquad (12)$$

Usually the condition:

$Q >> {}^{X_L}/\, Z_o$ is a valid approximation for most NMR probe circuits.

The solutions then reduce to:

$$C_{C1} = [\, 2\pi f_o \;(X_L - \sqrt{Z_o R_L}\,)\,]^{-1} \qquad (12a)$$

and

$$C_{C2} = [\, 2\pi f_o \;\sqrt{Z_o R_L}\,]^{-1} \qquad (12b)$$

IIC. The Hybrid Tuned Circuit

The circuit diagram is shown in Figure 3. Capacitor, C_{C1}, and transmission line, D1, are used to tune a load, X_L and R_L, to an input impedance $Z_{IN} = Z_o$, $\phi_{IN} = 0.0°$ at frequency f_o.

The impedance, Z_D, measured at the open end of a transmission line of length D terminated in a load, X_L and R_L, can be shown[2] to be:

$$Z_D = \frac{Z_o\;[\,(R_L + j\,X_L) + Z_o \tanh \gamma D\,]}{[\,Z_o + (R_L + j\,X_L) \tanh \gamma D]} \qquad (14)$$

$$\gamma = \alpha + j\,\beta, \quad \beta = {}^{2\pi}/\lambda_{\text{ cable}}$$

Z_o (ohms) is the characteristic impedance of the transmission line, α(nepers/meter) is the attenuation factor and β(radians/meter) is the phase factor. The length of the transmission line D' equals:

$$D' = \frac{(VF)\; c\; D}{f_o} \qquad (15)$$

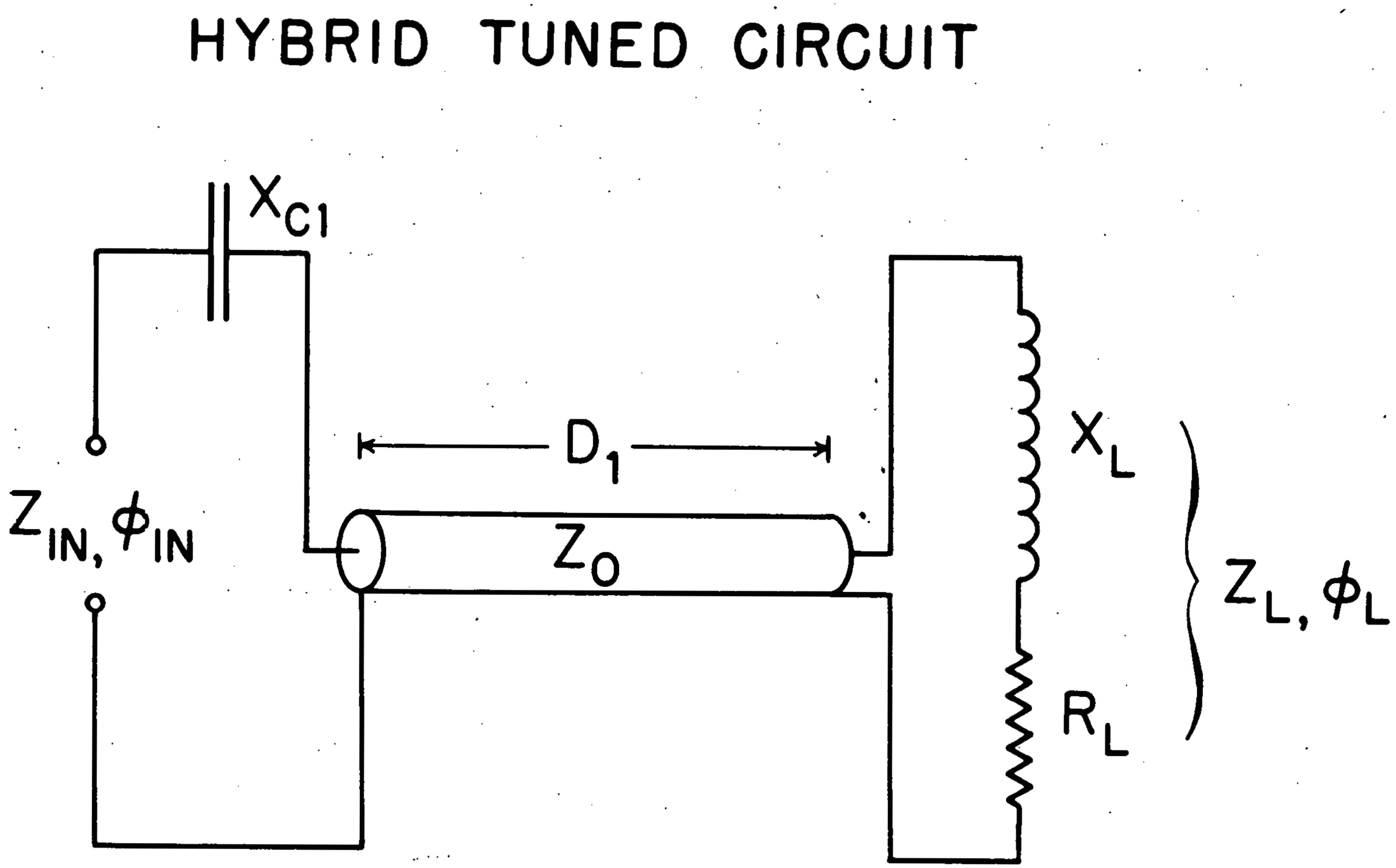


Fig. 3. Circuit diagram of the hybrid tuned circuit. A load, inductive reactance X_L and resistance R_L, is tuned to input impedance (Z_{IN}, ϕ_{IN}) at frequency f_o by transmission line D_1 and capacitive reactance X_{C1}.

where VF is the velocity factor of the cable, c is the speed of light, and D is the length of the cable in wavelengths at frequency, f_o. The attenuation factor, α, is frequency dependent. For small lengths of foamed polyethylene dielectric cable at frequencies below 100 MHz, the assumptions that $\alpha = 0.0$ and the characteristic impedance, Z_o, is purely resistive (i.e., a real number) are good approximations. Furthermore if D is expressed in wavelengths of cable at f_o then equation 14 reduces to

$$Z_D = \frac{Z_o (R_L + j X_L) + j Z_o \tan 2 \pi D\lambda}{Z_o + j (R_L + j X_L) \tan 2 \pi D\lambda} \tag{16}$$

Assuming lossless cable, $\alpha = 0$, and a purely resistive characteristic impedance, Z_o, treating Z_D as a circuit impedance, and using standard linear circuit analysis, the input impedance, Z_{IN}, of the hybrid tuned circuit can be shown to be:

$$Z_{IN} = -j\, X_{C1} + \frac{Zo[R_L + j (Z_o \tan (2 \pi D_1) + X_L)]}{(Z_o - X_L \tan 2\pi D_1) + j (R_L \tan 2\pi D_1)} \tag{17}$$

The conditions:

Real $(Z_{IN}) = Z_o$

Imaginary $(Z_{IN}) = 0.0$

will result in $Z_{IN} = Z_o$, $\phi_{IN} = 0.0°$ at f_o. Note, here the input impedance is tuned to the characteristic impedance of the cable. With these conditions it can be shown that:

$$D_1 = \frac{1}{2\pi} \tan^{-1} \left(\frac{Z_o X_L - \sqrt{Z_o R_L (R_L^2 + X_L^2 + Z_o^2 - 2 Z_o R_L)}}{X_L^2 + R_L^2 - Z_o R_L} \right) \tag{18}$$

$$C_{C1} = \left[\frac{2\pi f_o Z_o \left[X_L Z_o + (Z_o^2 - X_L^2 - R_L^2) \tan 2\pi D_1 - X_L Z_o \tan^2 2\pi D_1 \right]}{(Z_o - X_L \tan 2\pi D_1)^2 + (R_L \tan 2\pi D_1)^2} \right]^{-1} \qquad (19)$$

D_1 will be calculated in wavelengths of cable at f_o. This value can be converted to a length of cable with equation 15. Since the attenuation factor, α, will always be greater than zero, the length, D_1, will be slightly shorter and the value of C_{C1}, slightly larger than predicted with these equations.

IID. The Shorted-Stub Tuned Circuit

The circuit diagram is shown in Figure 4. Two lengths of transmission line, D_1 and D_2, are used to tune a load, X_L and R_L, to an input impedance $Z_{IN} = Z_o$, $\phi_{IN} = 0.0°$, at frequency, f_o. Length D_2 is in parallel with length D_1 and its far end is shorted. Length D_2 is referred to as a shorted-stub. This design is similar to IIC, with the stub replacing capacitor C_1. Assuming lossless cable, $\alpha = 0$, with a purely resistive characteristic impedance, Z_o, the input admittance Y_{IN} can be shown to be

$$Y_{IN} = \frac{-j}{Z_o \tan 2\pi D_2} + \frac{(Z_o - X_L \tan 2\pi D_1) + j R_L \tan 2\pi D_1}{R_L + j\left[Z_o \tan(2\pi D_1) + X_L\right]} \qquad (20)$$

The conditions:

Real $(Y_{IN}) = {}^1/Z_o$

Imaginary (second term of equation 20) >0.0

Imaginary $(Y_{IN}) = 0.0$

will result in $Z_{IN} = {}^1/Y_{IN} = Z_o$, $\phi_{IN} = 0.0°$ at f_o. The condition, imaginary (second term of equation 20) >0.0, will yield the shorter of the two possible lengths of D_1 that are solutions. With these conditions it can be shown that:

SHORTED-STUB TUNED CIRCUIT

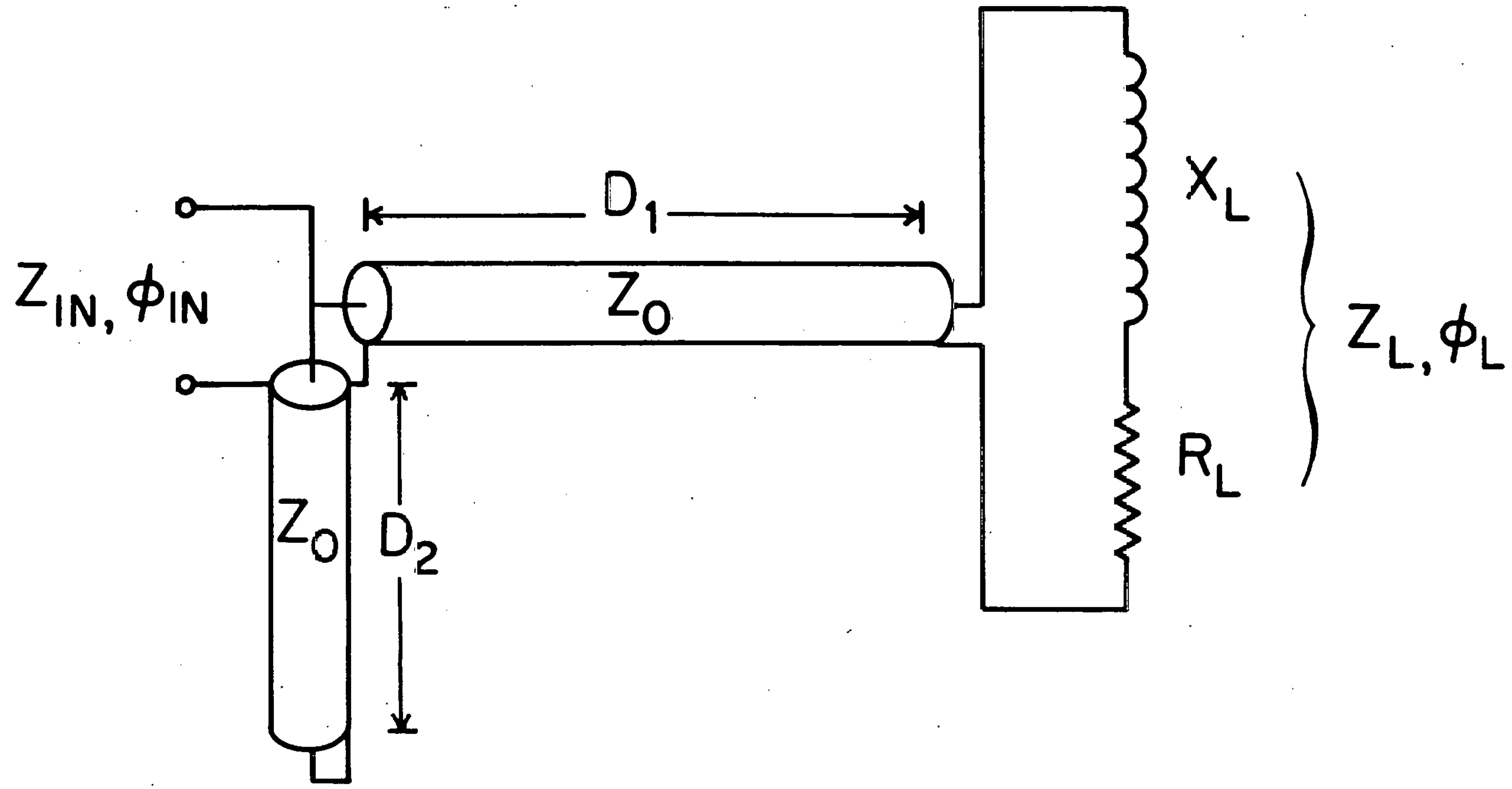


Fig. 4. Circuit diagram of the shorted stub tuned circuit. A load, inductive reactance X_L and resistance R_L, is tuned to input impedance (Z_{IN}, ϕ_{IN}) at frequency f_o by transmission lines D_1 and D_2.

$$D_1 = 0.5 + {}^1/_{2\pi} \tan^{-1} \left[\frac{X_L Z_o + \sqrt{Z_o R_L (Z_o^2 + X_L^2 + R_L^2 - 2 Z_o R_L)}}{Z_o R_L - Z_o^2} \right] \quad (21)$$

$$D_2 = {}^1/_{2\pi} \tan^{-1} \left[\frac{R_L^2 + (Z_o \tan (2\pi D_1) + X_L)^2}{(R_L^2 + X_L^2 - Z_o^2) \tan 2\pi D_1 + X_L Z_o (\tan^2 2\pi D_1) - X_L Z_o} \right] (22)$$

D_1 and D_2 are expressed in wavelengths of cable at f_o. Since the attenuation factor, α, is greater than zero, for a highly inductive load, the length D_1 will be slightly shorter and the length, D_2, slightly longer than predicted above.

Figures 5, 6, 7 and 8 present general design graphs that were drawn using the computer program described in Appendix A. These curves are graphical solutions of equations 8, 9, 11, 12, 18, 19, 21 and 22 for $Z_{IN} = 50.0$ ohms, $\phi_{IN} = 0.0°$ and Q's of 57 ($\phi_L = 89.0°$) and 19.1 ($\phi_L = 87.0°$).

Design graphs, which are frequency independent, provide a graphical relationship between the impedance of the load and the reactances and/or cable wavelengths of the tuning components. These curves allow quick estimates for the approximate values of the tuning components. The horizontal axis, $Z_L = \sqrt{X_L^2 + R_L^2}$, represents the magnitude of the impedance of the load as would be read on a vector impedance meter. For highly inductive loads $Z_L \approx X_L$. The vertical axes are in capacitive reactance or wavelengths of cable. These values can be converted to capacitance and lengths of cable using equation 1 (or 2) and 15 respectively.

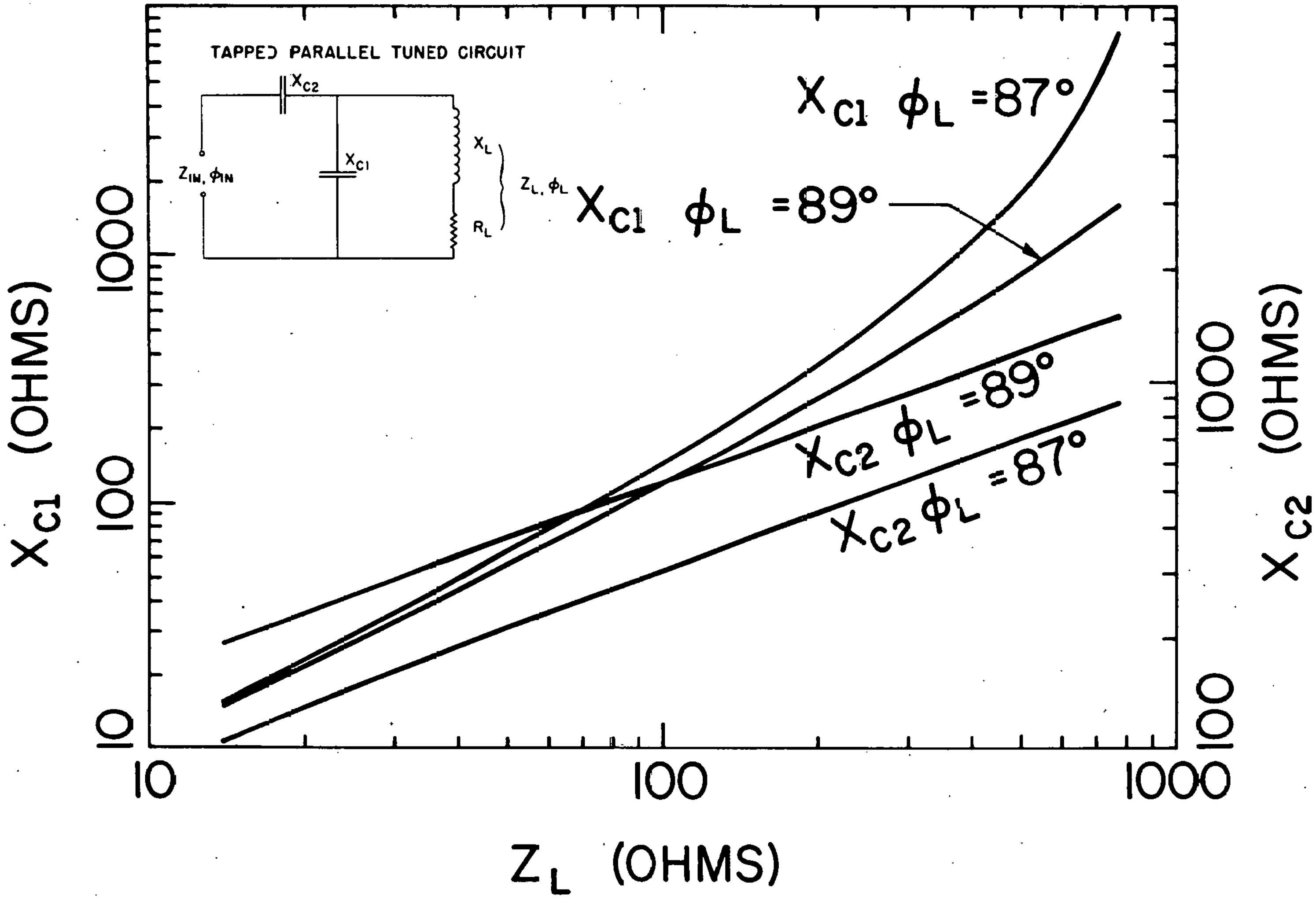


Fig. 5. Design graph for the tapped parallel tuned circuit. The graph yields capacitive reactances X_{C1} and X_{C2} required to tune a load Z_L to input impedance (Z_{IN} = 50.0 Ω, ϕ_{IN} = 0.0°) for Q's of 57 (ϕ_L = 89.0°) and 19.1 (ϕ_L = 87.0°).

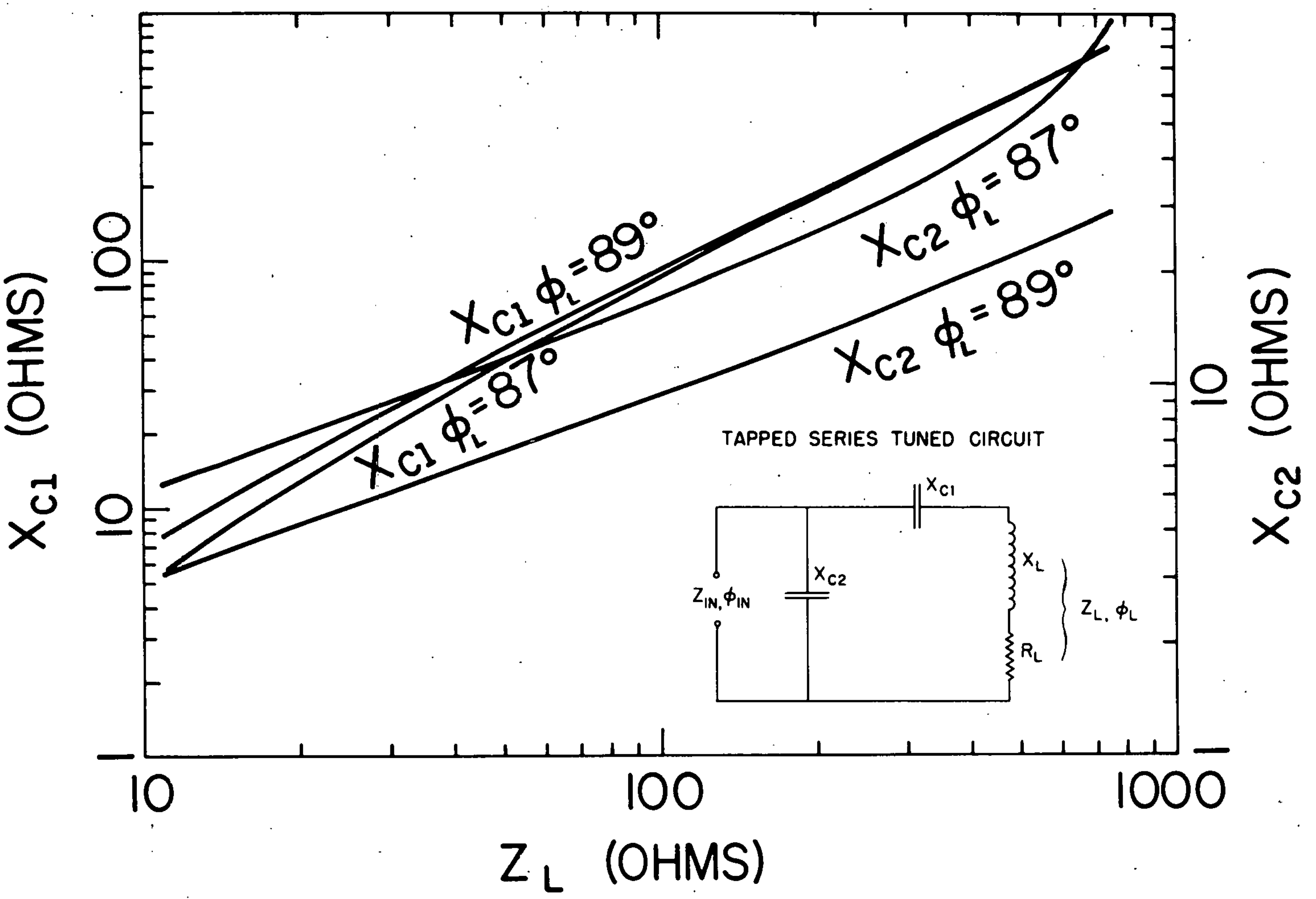


Fig. 6. Design graph for the tapped series tuned circuit. The graph yields capacitive reactances X_{C1} and X_{C2} required to tune a load Z_L to input impedance ($Z_{IN} = 50.0\ \Omega$, $\phi_{IN} = 0.0°$) for Q's of 57 ($\phi_L = 89.0°$) and 19.1 ($\phi_L = 87.0°$).

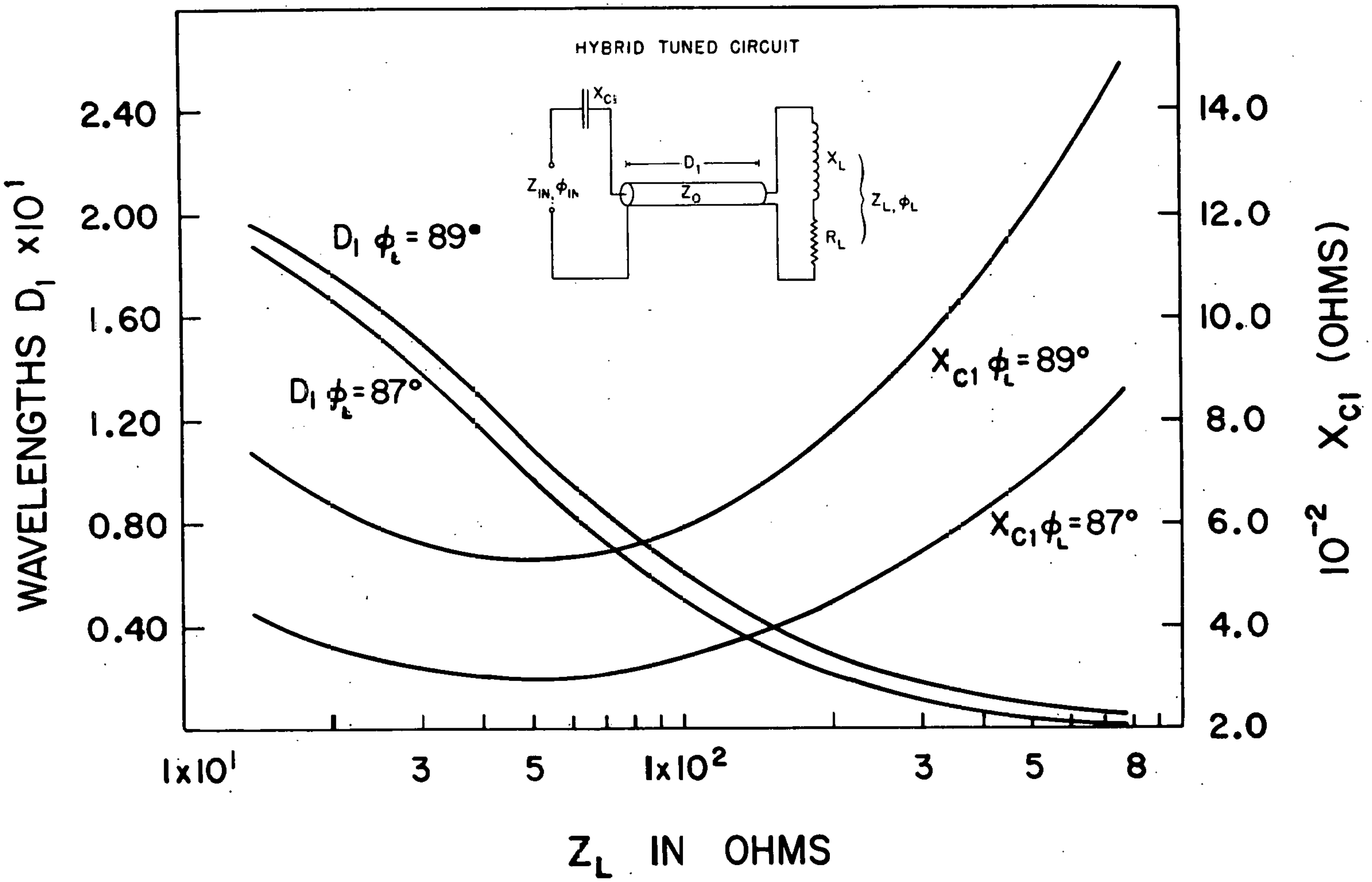


Fig. 7. Design graph for the hybrid tuned circuit. The graph yields wavelength of transmission line, D_1, and capacitive reactance X_{C1} required to tune a load Z_L to input impedance ($Z_{IN} = 50.0\,\Omega$, $\phi_{IN} = 0.0°$) for Q's of 57 ($\phi_L = 89.0°$) and 19.1 ($\phi_L = 87.0°$).

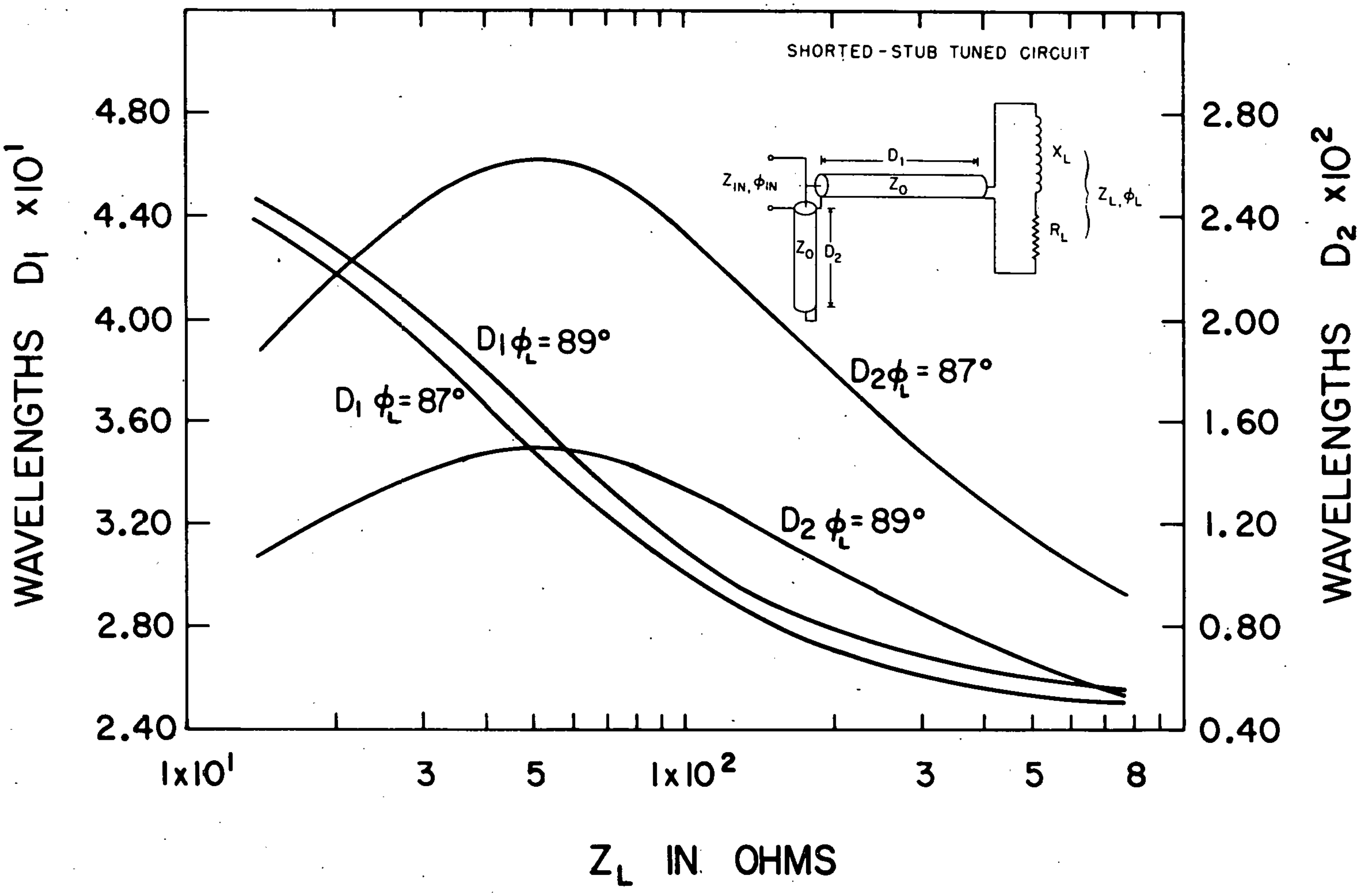


Fig. 8. Design graph for the shorted stub tuned circuit. The graph yields wavelengths of transmission line, D_1 and D_2 required to tune a load Z_L to input impedance ($Z_{IN} = 50.0\ \Omega$, $\phi_{IN} = 0.0°$) for Q's of 57 ($\phi_L = 89.0°$) and 19.1 ($\phi_L = 87.0°$).

IIE. Frequency Response

The magnitude of the input impedance, Z_{IN}, and phase angle, ϕ_{IN}, can be obtained from the equations (7, 10, 17, and 20) of the input impedance of each circuit. Let X_L, X_{C1}, X_{C2}, D_1 and D_2 represent the appropriate values for $Z_{IN} = Z_o$, $\phi_{IN} = 0.0°$ at f_o. The frequency dependence of these terms at any frequency, f, can be incorporated into each equation by replacing these terms with:

$$X_L(a), \quad X_{C1}\left(\frac{1}{a}\right), \quad X_{C2}\left(\frac{1}{a}\right), \; D_1(a), \; D_2\,(a),$$

with $a = f/f_o$. At a frequency, f, the magnitude of the input impedance is:

$$|Z_{IN}| = \sqrt{\text{Real}^2(Z_{IN}) + \text{Imaginary}^2(Z_{IN})}$$

and the phase angle is:

$$\phi_{IN} = \tan^{-1}\left(\frac{\text{Imaginary }(Z_{IN})}{\text{Real }(Z_{IN})}\right)$$

$|Z_{IN}|$ and ϕ_{IN} are the values that would be read on a vector impedance meter as the frequency is swept. The frequency dependent equations for each circuit are:

Tapped Parallel-Tuned Circuit

$a = f/f_o$

$$Z_{IN} = -j\,\frac{X_{C2}}{a} + \frac{X_{C1}\,X_L - j\,\dfrac{X_{C1}\,R_L}{a}}{R_L + j\,(a\,X_L - \dfrac{X_{C1}}{a})} \qquad (23)$$

Tapped Series-Tuned Circuit

$Z_{IN} = {}^{1}/Y_{IN}$, $a = {}^{f}/f_{o}$

$$Y_{IN} = \frac{j\,a}{X_{C2}} + \frac{1}{R_L + j\,(aX_L - \frac{X_{C1}}{a})} \qquad (24)$$

Hybrid Tuned Circuit

$a = {}^{f}/f_{o}$

$$Z_{IN} = -j\,\frac{X_{C1}}{a} + \frac{Z_o\,[\,R_L + j\,(Z_o \tan(2\pi\,a\,D_1) + a\,X_L\,)\,]}{(Z_o - a\,X_L \tan(2\pi\,a\,D_1)) + j\,(R_L \tan(2\pi\,a\,D_1))} \qquad (25)$$

Shorted-Stub Tuned Circuit

$Z_{IN} = {}^{1}/Y_{IN}$ $a = {}^{f}/f_{o}$

$$Y_{IN} = \frac{-j}{Z_o \tan(2\pi\,a\,D_2)} + \frac{(\,Z_o - a\,X_L \tan(2\pi\,a\,D_1) + j\,R_L \tan(2\pi\,a\,D_1))}{R_L + j\,(Z_o \tan(2\pi\,a\,D_1) + a\,X_L)} \qquad (26)$$

The real and imaginary response of the above equations can be determined quite easily on the computer. The computer program described in Appendix A will calculate both the impedance and phase angle response for all four circuits described in this report.

The ideal impedance and phase response of each circuit are shown in Figures 9, 10, 11, and 12 respectively. Identical loads which consist of a $0.42\ 10^{-6}$ Henry inductor in series with a 7.75 ohm resistor (Q = 19.1) are tuned to $Z_{IN} = 50.0$ ohms, $\phi_{IN} = 0.0°$ at $f_o = 56$ MHz. The left axis represents the magnitude of the input impedance and the right axis represents the phase angle of the input impedance.

III. Experimental Comparison of the Four Circuits

In order to evaluate the relative performances of each circuit, an experimental comparison of the relative pulse widths, ringdowns and signal/noise ratios was made. All measurements were made with the same load (X_L and R_L) fixed in one position in the same probe box. All circuits were tuned to $Z_{IN} = 50.0$ ohms, $\phi_{IN} = 0.0°$ at $f_o = 56.0$ MHz. No external matching networks were used. The input power, receiver sensitivity and receiver bandwidth were constant throughout the experiment. All measurements were made over a single three hour period.

A 29 mm long coil made of 19 turns of No. 18 wire wound to a 5 mm inside diameter was used. The inductance of the coil was measured as 0.38 μH. The load consisted of this coil in series with a 1 watt 5 ohm (D.C. resistance) resistor.

Both the coil and resistor were permanently mounted in a 6'' x 3'' x 1$\frac{3}{4}$'' aluminum probe box. All components were attached at identical points to the load. All components except for the length D_1 and D_2 of the shorted-stub circuit were enclosed in the probe box. The impedance of the load in the box was measured to be $Z_L = 148$ ohms, $\phi_L = 87.0°$. This impedance is equivalent to a $X_L = 148$ ohm (0.42 μH) inductor in series with a $R_L = 7.75$ ohm resistor. Note here that the value of inductance increases because of the inductive contribution from the resistor. Also, the value of the resistance increases because of the skin effect and resistance from the inductor. The Q of the load equals 19.1.

The sample consisted of a 0.06 ml of water doped with $FeCl_3$. T_1 and T_2 were equal and measured to be 4 msec. The sample was enclosed in a spherical bulb and was located in the same position in the coil for all measurements. Hydrogen resonance occurred at 56.020 MHz in the 14 K Gauss magnetic field. The transmitter consisted of an IFI 5000 wideband amplifier driving an IFI 408 distributed amplifier. The rms output power at the probe was measured at 100 watts and was constant throughout the experiment. The receiver was made up of Spectrum Microwave preamps and a D.C. amplifier. The total gain was 70 dB. Ceramic (7-45 pf) trimmers and/or microwave grade 50 pf fixed ceramic capacitors were used. Cable lengths were made from RG 58 C/U for which $Z_o = 50$ ohms, VF = 0.66 and α = 3dB/30.5 meters at 56 MHz. Impedances were measured on a HP 4815A vector impedance meter. Pulse widths and ringdown times were measured on a HP 18A scope. All measured values of capacitance and inductance were corrected for the residual vector probe impedance which was approximately 8.0 ohms <90° at 56.0 MHz.

Pulse widths were measured for a series of 50 90° pulses. Ringdown was measured as the total time from the trailing edge of the 90° pulse to the point where receiver noise predominated. Signal/noise ratios were measured as the ratio of the signal amplitude following a 90° pulse (and a delay of 10 μsec to allow for ringdown) to the average value of noise intensity at a point on the baseline where no signal was present. S/N values are the average of ten trials. Table I is a summary of the component values, relative pulse widths, relative ringdown times and relative signal/

Table 1

Experimental Comparison of the Values of Tuning Components, Relative Pulse Widths, Relative Ringdown Times and Relative Signal/Noise Ratios for Four Circuits.

Circuit	Values for Z_{IN}=50 Ω, ϕ_{IN}= 0.0° at f_o = 56 MHz	Relative Pulse Width	Relative Ringdown	Relative Signal/Noise
	Cap. in pf (± 5%) Length in cm. (± 1%)	(± . 0.02)	(± 0.1)	(± .03)
Tapped parallel tuned	C1 = 13.9 (11.7) C2 = 10.0 (7.6)	1.01	1.03	0.95
Tapped series tuned	C1 = 26.3 (21.9) C2 = 117.0 (132.7)	1.04	1.09	0.89
Hybrid tuned	C1 = 9.3 (7.3) D_1 = 11.5 (11.3)	1.00	1.00	1.00
Stub tuned	D_1 = 98.5 (99.6) D_2 = 7.9 (7.2)	1.27	1.00	0.91

min. pulse width = 3.00 μsec. min. ringdown = 1.59 μsec. min. signal/noise = $^{34}/_1$

Estimated values of components appear in parentheses and are for Z_{IN} = 50.0 Ω , ϕ_{IN} = 0.0°, X_L = 148 Ω, R_L = 7.75, Q_L = 19.1 and VF = 0.66.

noise ratios. Values are relative to the hybrid tuned circuit. The component values were estimated using $X_L = 148$ ohms, $R_L = 7.75$ ohms, $Q = 19.1$, $VF = 0.66$, $f_o = 56.0$ MHz and equations 8, 9, 11, 12, 18, 19, 21, and 22. These predicted values are given in parentheses next to the actual value.

IV. Circuit Losses and Effective Q's

The quality factor Q has been defined as $Q = X_L/R_L$. Q is related to the circuit's ability to store energy. A ringdown time, $\text{tau} = \frac{21\,Q}{\pi f_o}$ (27) can be considered as the approximate time required for the RF voltage across the load to exponentially decay from 1000 volts to 1.0 microvolt. Specification of an accurate Q is very important if relative comparisons between the four circuits (with respect to power efficiency, ringdown time and signal/noise) are to be meaningful.

An accurate method for calculating the effective Q of the entire probe circuit is to consider all capacitors, inductors and cables as being "ideal" and to refer all losses - whatever the source, to the load resistor, R_L which is in series with the inductor. For example, the actual value of the capacitor C_{C2} which is required to tune a tapped series tuned circuit to input impedance, $Z_{IN} = Z_o$, can be used to determine the effective Q for this circuit. For the tapped series tuned circuit the value of capacitor C_{C2} is solely determined by the resistive losses of the load, R_L (equation 15). As the resistive losses decrease (Q increases), the value of C_{C2} required to tune a fixed input impedance $Z_{IN} = Z_o$, increases. By rearranging equation 12, an effective Q, $Q_{eff} = \frac{X_L}{R_{eff}}$, can be defined:

$$Q_{eff} = 4\pi^2 f_o^2 X_L Z_o C_{C2}^2 + X_L/Z_o \qquad (28)$$

For the case where $Q_{eff} >> X_L/Z_o$ which is usually true for most NMR probes:

$$Q_{eff} \cong 4\pi^2 f_o^2 X_L Z_o C_{C2}^2 \qquad (28a)$$

X_L is the inductive reactance of the NMR coil measured at frequency, f_o. However C_{C2} is the actual measured capacitance required to tune the input impedance to $Z_{IN} = Z_o$ at f_o. In effect the above treatment lumps all circuit losses from all components into the load resistance, R_{eff}. Components are now treated as lossless. Capacitance C_{C2} may now be considered that value required to tune a circuit with load:

$$X_L,\ R_{eff} \text{ and } Q_{eff} \text{ to } Z_{IN} = Z_o,\quad \phi_{IN} = 0.0° \text{ at } f_o.$$

Of course the actual capacitor, C_{C2}, has ohmic losses. Since $R_{eff} = X_L/Q_{eff}$, all RF current flowing in the inductor will "feel" a resistance, R_{eff}. Such a treatment is very desirable and valuable since the RF current flowing in the inductor originates from the RF pulse or the NMR signal. A similar treatment can be applied to the remaining three circuits.

Tapped Parallel Tuned Circuit:

$$Q_{eff} >> \frac{X_L Z_o}{X_{C1}^2} \qquad X_{C1} = (2\pi f_o C_{C1})^{-1}$$

$$Q_{eff} \cong \frac{X_L}{Z_o} (1 - 2\pi f_o X_L C_{C1})^{-2} \qquad (29)$$

Hybrid Tuned Circuit:

$A = \tan 2\pi D_1$, $\quad Q_{eff} >> \frac{X_L}{Z_o(1+\frac{1}{A^2})}$

$$Q_{eff} \cong \frac{Z_o X_L (1 + A^2)}{Z_o^2 - 2 Z_o X_L A + X_L^2 A^2} \qquad (30)$$

Shorted Stub Tuned Circuit:

$A = \tan 2\pi D_1$, $\quad Q_{eff} >> \frac{X_L}{Z_o(1+A^2)}$

$$Q_{eff} \cong \frac{Z_o X_L (1 + A^2)}{Z_o^2 A^2 + 2 X_L Z_o A + X_L^2} \qquad (31)$$

For the hybrid and shorted stub tuned circuits, D_1 is the actual measured length of cable D_1 in wavelength at frequency, f_o. Also Z_o is both the input impedance and the characteristic impedance of the cable. For most probes, the effective Q's are usually well above the lower limits of the inequalities for which all four equations are valid.

V. Discussion

This section will attempt to evaluate the actual performances of the four circuits.

The actual value of the components (Table I) and the estimated values from equations 8, 9, 11, 12, 18, 19, 21, 22 agree fairly well. Particularly, the actual cable lengths are very close to the estimates. The assumption that the cable attenuation factor, α, equals zero appears to be fairly accurate for these lengths of cables.

Va. Frequency Response

The experimentally measured impedance and phase responses agreed qualitatively with the theoretical responses shown in figs. 9, 10, 11 and 12. For all four circuits the average quantitative agreement was roughly within ± 5% in the region of 56.0 MHz but fell off to ± 15% at frequencies less than 52.0 MHz and greater than 60.0 MHz.

Such behavior, which may be regarded as a sign of non-ideality, is expected. For instance, the inductor is strictly linear only near 56.0 MHz. Contributions to non ideality originate in the non-theoretical responses and finite Q's of the capacitors, cable and coil. Additionally distributed reactances are always present.

The importance of response curves rests with their use to judge the feasibility of attempting a specific design. The location of low impedance and high impedance resonances ($\phi_{IN} = 0.0°$ in both cases) can be checked in relation to the tuning frequency.

For instance, a common problem in designing the tapped series tuned circuit is that low impedance resonance occurs slightly below the tuning frequency. This low impedance resonance moves farther down frequency as the Q is lowered. However for high enough Q's, it may interfere with the tuning at the desired frequency. Frequency response graphs are useful in anticipating and avoiding this problem.

Interestingly, the theoretical frequency responses of both the tapped parallel tuned and hybrid tuned circuits are virtually identical. This

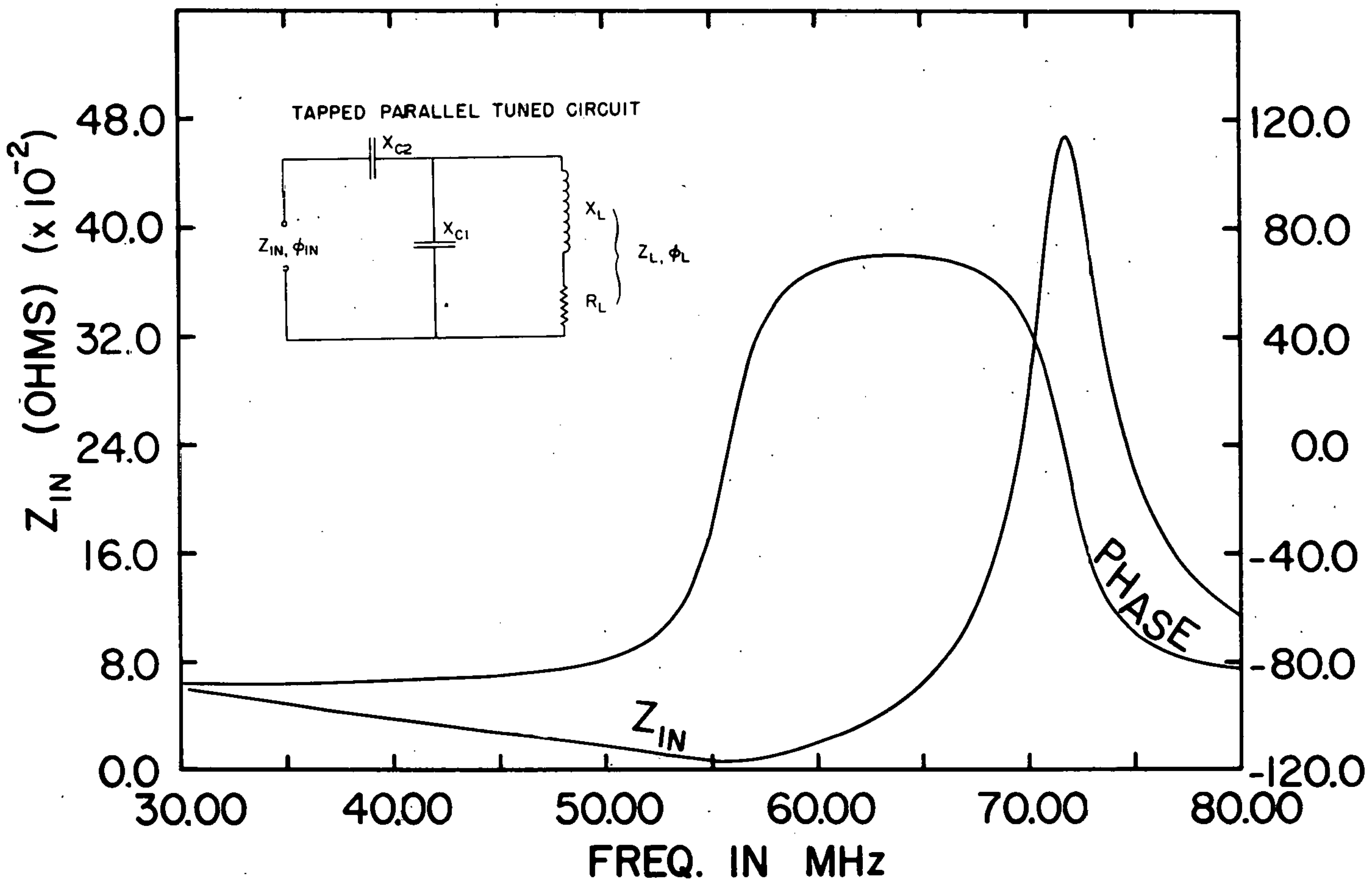


Fig. 9. Theoretical frequency response for a tapped parallel tuned circuit tuned to (Z_{IN} = 50.0 Ω, ϕ_{IN} = 0.0°) at f_o = 56 MHz where X_L = 148 Ω, R_L = 7.75 Ω, X_{C1} = 243.6 Ω, X_{C2} = 373.1 Ω and Q_L = 19.1.

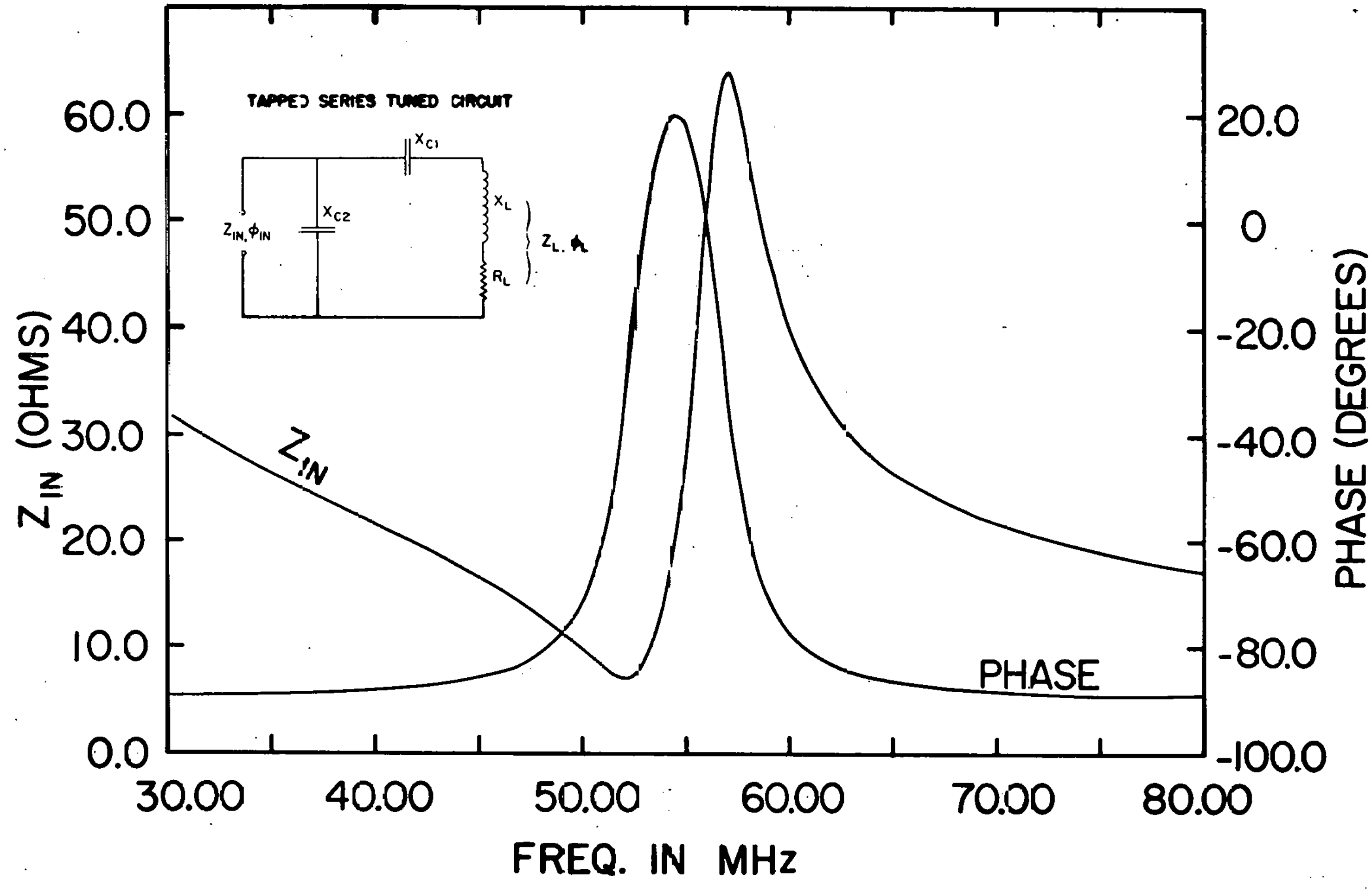


Fig. 10. Theoretical frequency response for a tapped series tuned circuit tuned to (Z_{IN} = 50.0 Ω, ϕ_{IN} = 0.0°) at f_o = 56 MHz where X_L = 148 Ω, R_L = 7.75 Ω, X_{C1} = 129.9 Ω X_{C2} = 21.41 Ω and Q_L = 19.1.

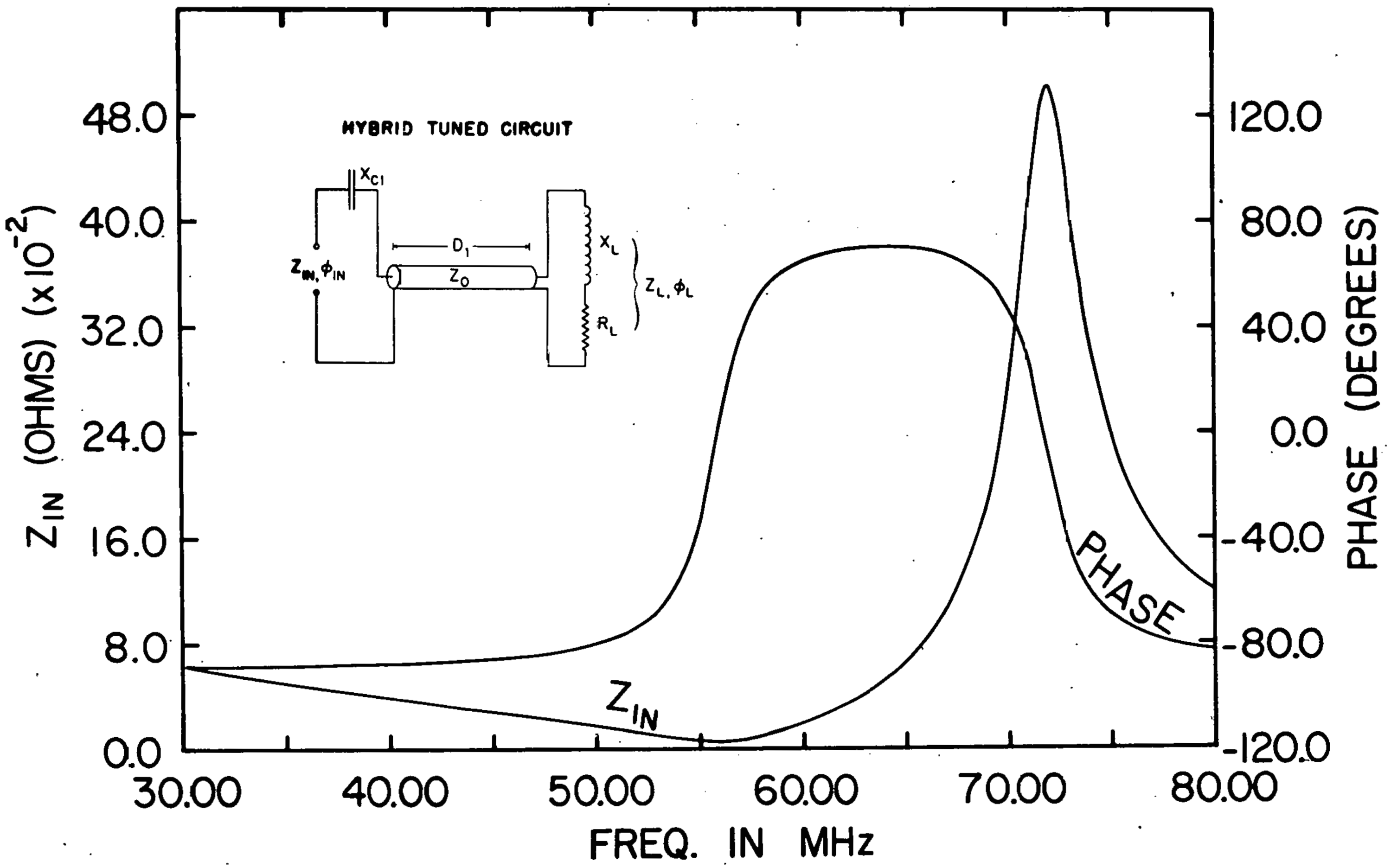


Fig. 11. Theoretical frequency response for a hybrid tuned circuit tuned to (Z_{IN} = 50.0 Ω, ϕ_{IN} = 0.0°) at f_o = 56 MHz where X_L = 148 Ω, R_L = 7.75 Ω, D_1 = 0.032 λ, X_{C1} = 391.0 Ω, and Q_L = 19.1.

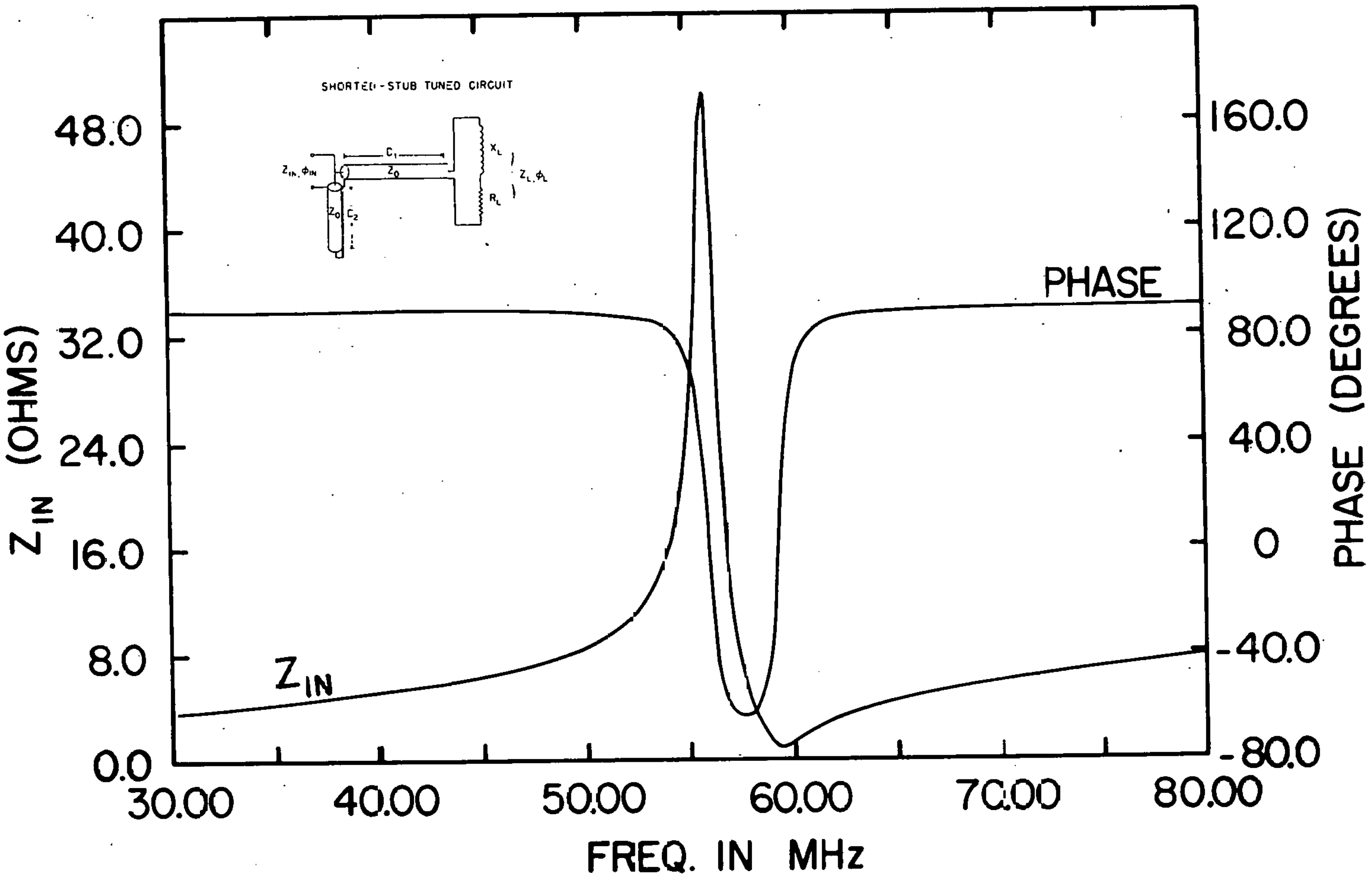


Fig. 12. Theoretical frequency response for a shorted-stub tuned circuit tuned to (Z_{IN} = 50.0 Ω, ϕ_{IN} = 0.0°) at f_o = 56 MHz where X_L = 148 Ω, R_L = 7.75 Ω, D_1 = 0.282 λ, D_2 = 0.0202 λ and Q_L = 19.1.

behavior is not unexpected since cable D_1 is short enough to be considered as a small capacitor in parallel with the coil (i.e. almost a tapped parallel tuned circuit) at this frequency.

Vb. Pulse Widths, Effective Q's and Circuit Efficiencies

For these designs and choice of components, both the tapped parallel tuned and hybrid tuned circuits had the smallest 90.0° pulse widths and thus the best efficiencies. The tapped series tuned circuit was slightly poorer, while the shorted stub tuned circuit was noticeably the worst.

All four circuits were designed to have Q's of 19.1. From equations 29, 28, 30 and 31, the effective Q, Q_{eff}, can be calculated for each circuit using the appropriate values from Table I. The effective Q's are: $Q_{TPTC} = 39 \pm 15$, $Q_{TSTC} = 15.5 \pm 2$, $Q_{HTC} = 20.7 \pm 1$, $Q_{SSTC} = 14.3 \pm 4$. The large uncertainty in Q_{TPTC} results from the small value of capacitor C_{C1}. Q_{eff} values, which can act as measures of power efficiency, are consistent with the observed pulse widths: highest Q circuits have the shortest pulse widths, lowest Q circuits have the longest pulse widths. It should be noted that choice of components strongly affects Q_{eff}. For instance the hybrid tuned circuit uses only one 7-45 pf ceramic variable capacitor and a small length of R658 C/U cable - a high Q_{eff} might be anticipated. The tapped series tuned circuit uses two 7-45 pf ceramic variable and two microwave grade 50 pf fixed capacitors - because of the inherent losses in such a large number of components a low Q_{eff} might be anticipated.

The large power inefficiency of the shorted stub tuned circuit results directly from the high but finite Q of the coaxial cable (RG58 C/U). Since cable D_1 is terminated in a highly inductive load, not its characteristic impedance, a high standing wave pattern exists on this cable. Furthermore, since the length of cable D_1 is greater than a quarter-wavelength at 56 MHz, a current maximum will exist on cable D_1. Since the cable has losses (finite Q), this current maximum will cause large power dissipation. Also cable D_2 is relatively short with a very high admittance. The finite Q of this short cable will result in additional power losses.

Vc. Ringdown Times and Signal/Noise Ratios

The relative value of ringdown times as shown in Table I may be regarded as approximate since this type of measurement is subject to many sources of error. For Q = 19.1, ringdown times of the order of 2.3 microseconds (eq. 27) are expected. Ringdown times are more or less consistent with this value. In general, the lowest Q_{eff} circuits are expected to have shortest ringdowns and fastest recovery times. Signal/noise ratios are directly related to Q_{eff}. The highest Q_{eff} circuits should have the highest S/N ratios. The experimental data from Table I support this postulate. Both the tapped parallel and hybrid tuned circuits, which have somewhat higher Q_{eff}'s, have better S/N ratios. The tapped series tuned and shorted stub tuned circuits, which have lower Q_{eff}'s, have poorer S/N ratios.

Vd. NMR Probe Designs.

The choice of a particular circuit depends upon such factors as space requirements, quality and range of tuning components and type of applications. For multipulse operation where low Q_{eff} is required, both the tapped series tuned and hybrid tuned circuits are useful at higher frequencies. However at lower frequencies capacitor C_{C2} becomes very large for the tapped series tuned circuit thereby making the hybrid tuned and tapped parallel tuned circuits better choices. For strictly high Q circuits, the tapped parallel tuned circuit with very high Q capacitors is probably the best choice at all frequencies. Since the NMR coil is located at the end of a cable, both the hybrid tuned and shorted stub tuned circuits are useful for compact designs such as low temperature and lock probes. In this laboratory, the hybrid tuned circuit has been incorporated into compact NMR lock probes quite nicely. A diagram of one such probe is shown in fig. 13. The shorted stub probe is useful in applications where ruggedness is important and power inefficiency, acceptable - such as in liquid NMR. In this laboratory, both the tapped series tuned and hybrid tuned circuits have been incorporated into a compact single coil double resonance probe[3] for magic angle spinning of solids. A schematic diagram of this probe appears in fig. 14.

In general, as the experimentalist becomes more familiar with design techniques, construction of NMR probe circuits - whether for specific experiments or general use - will become easier.

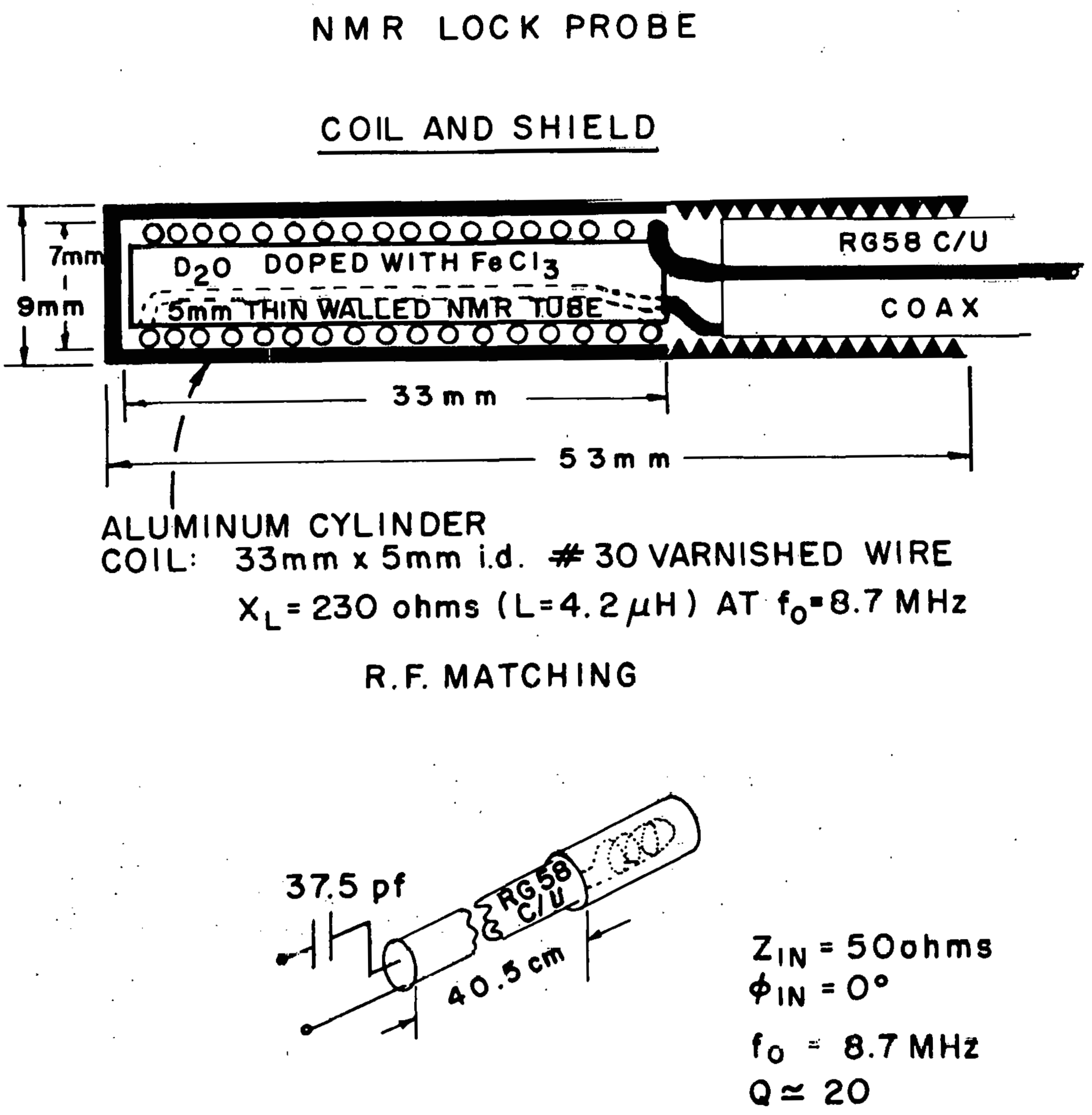
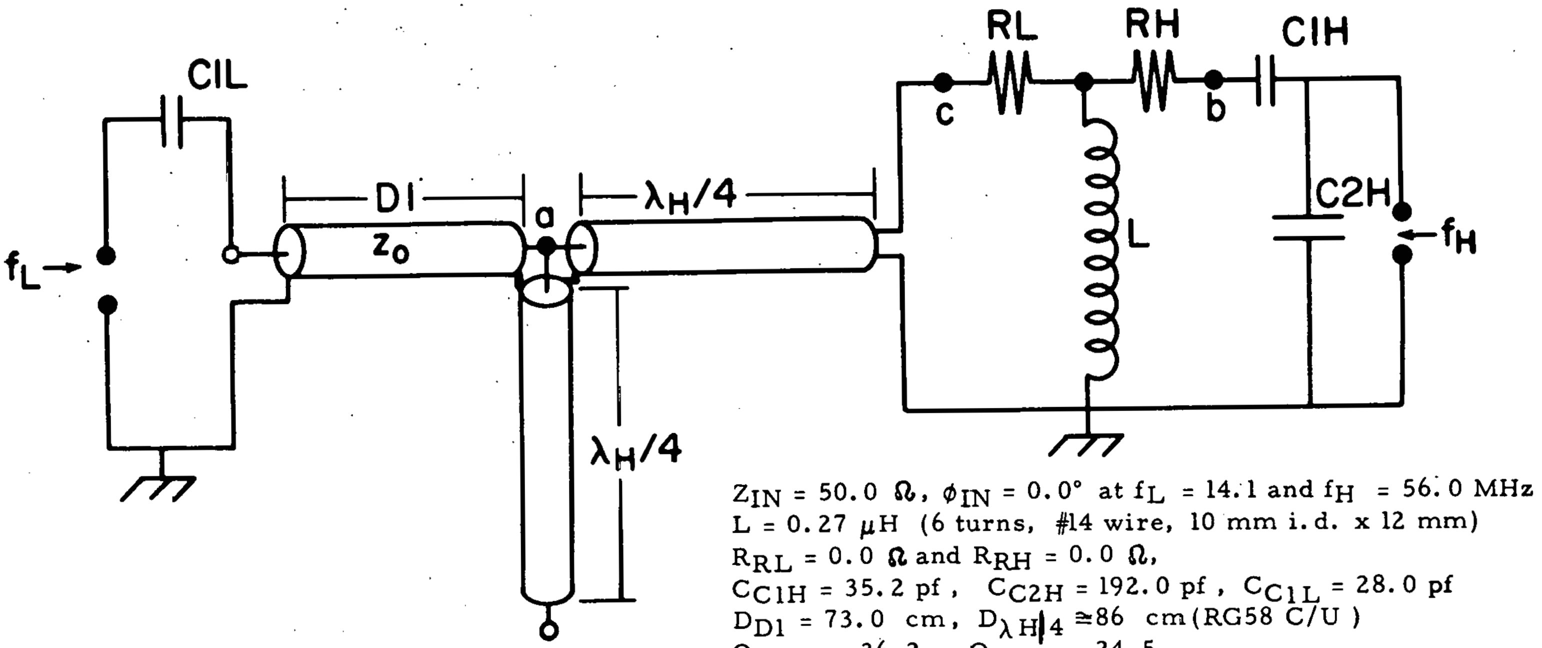


Fig. 13. Specifications for a compact NMR lock probe tuned with the hybrid tuned circuit.



Z_{IN} = 50.0 Ω, ϕ_{IN} = 0.0° at f_L = 14.1 and f_H = 56.0 MHz
L = 0.27 μH (6 turns, #14 wire, 10 mm i.d. x 12 mm)
R_{RL} = 0.0 Ω and R_{RH} = 0.0 Ω,
C_{C1H} = 35.2 pf, C_{C2H} = 192.0 pf, C_{C1L} = 28.0 pf
D_{D1} = 73.0 cm, $D_{\lambda H|4} \cong 86$ cm (RG58 C/U)
$Q_{eff, L}$ = 36.2, $Q_{eff, H}$ = 24.5

Fig. 14. Specifications for a single coil ^1H-^{13}C double resonance probe tuned with a tapped series tuned circuit and a hybrid tuned circuit.

VI. Summary

A discussion has been presented which has shown that the component values for four NMR probe circuits can be estimated with reasonably good accuracy. Frequency response curves have been shown to be useful in judging the feasibility of a particular design. A method has been presented which allows the effective circuit quality factor, Q_{eff}, to be calculated after the probe is assembled.

Experimental designs using the design techniques of this report have been found to yield good agreement with predicted results. Finally a FORTRAN Computer Program which will make the numerical calculations and draw the graphs described in this report, is presented in Appendix A.

Acknowledgement:

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Appendix A

FORTRAN COMPUTER PROGRAM:

DESIGN NUCLEAR MAGNETIC RESONANCE PROBE

A.I. INTRODUCTION

This appendix contains the entire computer program used to make all calculations and draw all graphs described in this report. The program is completely explained in the comment cards.

The program is written in FORTRAN IV[4,5] and will compile with an IBM FORTRAN IV level H compiler. A region of 224K is required for compilation and a region of 72K is required for execution. The program is written as a collection of subroutines, which may be incorporated into other FORTRAN programs.

All graphs are drawn with a local graphing program of the Iowa State Computer Center called SIMPLOTTER,[6]

The statement CALL GRAPH (N, X, Y, ...)

N: number of (x, y) points to be plotted

X: double precision array of X values

Y: double precision array of Y values

produces a disk data set which is passed to a subsequent step in the program where the actual drawing is done. SIMPLOTTER will produce both printer graphs and graphs drawn on a CAL COMP incremental plotter.

Included in this program is a low-level graphing subroutine, also named GRAPH, which will produce printer graphs similar to SIMPLOTTER.

A. II. FORTRAN COMPUTER PROGRAM

```
C
C
C   ******** DESIGN NUCLEAR MAGNETIC RESONANCE PROBE  ********
C
C
C     WRITTEN BY PAUL MURPHY, RESEARCH ASSISTANT, AMES LAB, JAN. 1978
C
C
C
C     THE PURPOSES OF THIS PROGRAM ARE:
C
C        1. TO CALCULATE THE VALUES OF CAPACITANCE AND/OR CABLE LENGTH
C           REQUIRED TO CONSTRUCT ANY ONE OF FOUR DIFFERENT
C           NUCLEAR MAGNETIC RESONANCE ( NMR ) PROBES.
C
C        2. TO CALCULATE THE THEORETICAL FREQUENCY RESPONSE OF
C           ANY ONE OF FOUR DIFFERENT NMR PROBES.
C
C        3. TO CALCULATE THEORETICAL DESIGN GRAPHS FOR ANY ONE OF
C           FOUR DIFFERENT NMR PROBES.
C
C     THE NAMES AND CIRCUIT DIAGRAMS OF THE FOUR NMR PROBE CIRCUITS
C     FOLLOW:
C
C
C              CIRCUIT DESCRIPTIONS:
C
C        XL = NMR COIL ( OR INDUCTIVE REACTANCE )
C        RL = LOAD RESISTOR ( OR RESISTANCE )
C        C = CAPACITOR ( OR CAPACITANCE )
C        D = CABLE OR TRANSMISSION LINE ( OR LENGTH ) WITH
C            CHARACTERISTIC IMPEDANCE, Z0 AT 0.0 DEGREES PHASE ANGLE
C        ZIN = INPUT IMPEDANCE OF THE PROBE AT 0.0 DEGREES PHASE ANGLE
C
C
C
C               TAPPED PARALLEL TUNED          TAPPED SERIES TUNED
C
C               *** C2 *********               ************** C1 **
C               *         *    *               *       *          *
C               *         *                    *       *
C                              XL                      *          XL
C               ZIN       C1                   ZIN
C                              *                       C2         *
C               *         *                    *
C               *         *    RL              *       *          RL
C               *         *                    *       *
C               *         *    *               *       *          *
C               ****************               ********************
C
C
C
C
C
C
```

```
C
C
C             HYBRID TUNED                   SHORTED STUB TUNED
C
C             ** C1 **           ******      ******         *********
C             *      *           *    *      *    *    D1   *       *
C             *      *      D1   *                * *********
C                    * ********* *    XL     ZIN  ***********       XL
C             ZIN    *************                * *********
C                      **********     *      *   ****       *       *
C             *       *         *             ******        *
C             *       *         *     RL         ***        *       RL
C             *       *         *                *** D2     *
C             *       *         *     *          ***        *       *
C             *********         *******          ***        *********
C                                                 **
C
C        CABLE D2 IS SHORTED AT THE FAR END.
C
C
C     THE EQUATIONS UPON WHICH ALL ALGORITHMS ARE BASED
C     IN THIS PROGRAM APPEAR IN THE PH.D. THESIS OF
C     PAUL MURPHY ( IOWA STATE UNIVERSITY, 1979 ) .
C
C
C     THESE RF MATCHING CIRCUITS ARE USED TO TUNE AN INDUCTOR
C     ( NMR COIL ) WITH INDUCTIVE REACTANCE, XL, TO THE INPUT
C     IMPEDANCE, ZIN WITH PHASE ANGLE = 0.0 DEGREES, AT
C     FREQUENCY, F0.  NORMALLY, ZIN IS EQUAL TO THE CHARACTERISTIC
C     IMPEDANCE, Z0, OF THE TRANSMISSION LINE FEEDING THE PROBE.
C
C     THIS TREATMENT ASSUMES THAT ALL POWER LOSSES CAN BE LUMPED
C     INTO THE LOAD RESISTOR, RL.  LOSSES RESULT FROM SUCH PHENOMENA
C     AS RADIATION, INDUCTIVE COUPLING, SKIN EFFECTS, DIELECTRIC
C     LOSSES AND NON IDEAL COMPONENTS.
C
C     THEREFORE ALL CAPACITORS, CABLES AND INDUCTORS WILL BE TREATED
C     AS IDEAL ( LOSSLESS ).  ALL LOSSES WILL BE ASSUMED TO BE
C     SUITABLY ACCOUNTED FOR IN THE LOAD RESISTOR, RL.
C     BECAUSE OF THIS APPROXIMATION, THE ACTUAL EXPERIMENTAL VALUE
C     OF RL WILL ALWAYS BE LESS FOR A GIVEN Q.
C
C     BY SELECTING THE PROGRAM CONTROL, IOPT = 0 , A STANDARD
C     CALCULATION AT A FIXED FREQUENCY, F0, CAN BE MADE.
C
C     BY SELECTING THE PROGRAM CONTROL, IOPT = 1, A GENERAL CALCULATION
C     CAN BE MADE.  THE DIFFERENT CALCULATIONS ARE EXPLAINED
C     WITH THE VARIABLE, IOPT , BELOW.
C
C     THE FREQUENCY RESPONSE OF EACH CIRCUIT BETWEEN THE LIMITS:
C     FL AND FH WILL BE CALCULATED AND GRAPHED FOR IOPT = 0 ONLY.
C
C
C     *****  INPUT PARAMETERS  *****
```

```
C
C      ENTER ONE VALUE PER CARD.
C      VARIABLE FORMAT APPEARS IN PARENTHESES FOLLOWING VARIABLE NAME.
C
C      REAL VALUES MUST CONTAIN DECIMAL POINT AND LIE WITHIN THE
C      FIRST 13 COLUMNS.
C      INTEGERS MUST LIE IN COLUMN 1 .
C
C
C
C      IOPT (I1): PROGRAM CONTROL VARIABLE.
C         IOPT = 0 SPECIFIES A NORMAL CALCULATION AT A SINGLE
C         FREQUENCY, F0.
C         IOPT = 1 SPECIFIES A GENERAL CALCULATION.
C         IN THE GENERAL CALCULATION, CAPACITIVE REACTANCE AND/OR
C         CABLE WAVELENGTH ARE CALCULATED AS A FUNCTION OF THE INDUCTIVE
C         REACTANCE OF THE COIL AT A FIXED QUALITY FACTOR, Q,
C         AND AT A FIXED INPUT IMPEDANCE,
C         ZIN AT PHASE ANGLE = 0.0 DEGREES.
C         THIS CALCULATION DOES NOT DEPEND ON FREQUENCY.
C         THE TABLES AND GRAPHS PRODUCED BY THIS CALCULATION CAN
C         BE USED TO CALCULATE COMPONENT VALUES AT ANY FREQUENCY.
C
C      ICIRC (I1): CIRCUIT SELECTOR VARIABLE.
C         THIS VARIABLE IS USED TO SELECT ANY ONE OR ALL FOUR
C         OF THE CIRCUITS TO BE ANALYZED.
C         ICIRC = 1 - TAPPED PARALLEL TUNED CIRCUIT ONLY.
C         ICIRC = 2 - TAPPED SERIES TUNED CIRCUIT ONLY.
C         ICIRC = 3 - HYBRID TUNED CIRCUIT ONLY.
C         ICIRC = 4 - SHORTED STUB TUNED CIRCUIT ONLY.
C         ICIRC = 5 - ALL FOUR CIRCUITS.
C
C      IPRINT (I1): PRINT CONTROL VARIABLE.
C         THIS VARIABLE CONTROLS THE PRINTING OF GRAPHED DATA.
C         IPRINT = 0 - NO GRAPHED DATA PRINTED.
C         IPRINT = 1 - ALL GRAPHED DATA PRINTED.
C
C
C      ***** NOTE: ENTER THE FOLLOWING VARIABLES IF IOPT = 0 .
C
C      F0 (D13.6): THE RESONANT FREQUENCY IN MHZ AT WHICH THE
C         PROBE IS TUNED TO ZIN OHMS AT 0.0 DEGREES PHASE ANGLE.
C
C      XL (D13.6): INDUCTIVE REACTANCE IN OHMS OF THE NMR COIL.
C         THIS VALUE IS MEASURED AT THE RESONANT FREQUENCY, F0.
C         THIS  VALUE IS EQUAL TO ZL*SIN( PHI ) WHERE ZL AND PHI
C         ARE THE VECTOR IMPEDANCE AND PHASE ANGLE MEASURED AT F0.
C         XL = 2*PI*F0*L WHERE L IS THE INDUCTANCE OF THE COIL.
C
C      Q (D13.6): THE QUALITY FACTOR OF THE PROBE.  Q = XL/RL .
C         THE PROBE RINGDOWN TIME, TAU, IS DEFINED AS THE TIME
C         REQUIRED FOR THE VOLTAGE ACROSS THE COIL TO EXPONENTIALLY
C         DECAY TO EXP(-21) = 7.6 * 10**(-10) OF ITS INITIAL VALUE.
C         TAU IS ROUGHLY THE TIME IT TAKES 1000.0 VOLTS TO DECAY TO
C         1.0 MICROVOLTS - APPROXIMATELY THE MAGNITUDE OF AN NMR SIGNAL.
C         TAU = 21*Q/(PI*F0) FOR THE CIRCUITS DESCRIBED IN THIS PROGRAM.
C         IN GENERAL LOW Q PROBES HAVE SHORTER RINGDOWN TIMES.
C         A TYPICAL LOW Q WOULD BE APPROXIMATELY 20.0 .
```

```
C           A TYPICAL HIGH Q WOULD BE APPROXIMATELY 150.0 .
C           IN GENERAL THE Q WILL REACH A MAXIMUM BUT FINITE VALUE
C           FOR RL = 0.0 .  THIS VALUE IS DETERMINED BY CIRCUIT LOSSES.
C
C        ZIN (D13.6): THE INPUT IMPEDANCE IN OHMS TO WHICH THE
C           PROBE IS TUNED AT FREQUENCY, F0.  NOTE: THIS IMPEDANCE IS
C           ALSO THE CHARACTERISTIC IMPEDANCE OF ALL CABLES WHICH ARE
C           USED AS TUNING ELEMENTS I.E. CABLES D1 AND D2.
C           THE PHASE ANGLE OF ZIN WILL ALWAYS EQUAL 0.0 DEGREES.
C
C        VF (D13.6): VELOCITY FACTOR OF CABLES D1 AND/OR D2.
C           THE VELOCITY FACTOR IS THE RELATIVE SPEED OF ELECTROMAGNETIC
C           WAVE PROPOGATION IN THE CABLE COMPARED TO THAT IN A VACUUM.
C           VF MUST BE > 0.0 AND < OR = 1.0.
C           THE VELOCITY FACTOR FOR RG58C/U CABLE IS APPROXIMATELY 0.66 .
C           ALL CABLE IS ASSUMED LOSSLESS ( ATTENUATION FACTOR, ALPHA =
C           0.0 DB/METER ).
C
C        FL (D13.6): THE LOWER FREQUENCY LIMIT IN MHZ OF THE FREQUENCY
C           RESPONSE GRAPHS.  FREQUENCY RESPONSE GRAPHS ARE: ZIN VS. FREQ.
C           AND PHASE ANGLE VS. FREQ.  ZIN AND PHASE ANGLE WOULD BE
C           THE INPUT IMPEDANCE AND PHASE ANGLE AS MEASURED ON A
C           VECTOR IMPEDANCE METER AT FREQUENCIES BETWEEN FL AND FH.
C
C        FH (D13.6): THE UPPER FREQUENCY LIMIT OF THE FREQUENCY
C           RESPONSE GRAPHS.  THE INTERVAL FH - FL SHOULD BE CHOSEN
C           TO INCLUDE F0.  THE FREQUENCY RESPONSE WILL BE:
C           IMPEDANCE = ZIN AND PHASE ANGLE = 0.0 DEGREES AT F0.
C
C        *****  EXAMPLE:
C
C           DESIGNING A PROBE AT A SINGLE FREQUENCY:
C
C           SUPPOSE THE INDUCTIVE REACTANCE OF AN NMR COIL IS
C           MEASURED TO BE XL = 145.0 OHMS AT F0 = 56.0 MHZ USING A
C           VECTOR IMPEDANCE METER.  AN INPUT IMPEDANCE ZIN = 50.0 OHMS
C           AT F0 = 56.0 MHZ WITH A Q = 19.1 IS DESIRED USING A TAPPED
C           SERIES TUNED CIRCUIT.
C           THE THEORETICAL FREQUENCY RESPONSE BETWEEN FL = 50.0 MHZ
C           AND FH = 62.0 MHZ IS DESIRED TO COMPARED WITH THE ACTUAL
C           EXPERIMENTALLY MEASURED FREQUENCY RESPONSE.
C
C           THE PROGRAM WILL CALCULATE RL = 7.59 OHMS AND
C           C1 = 22.37 PICOFARADS AND C2 = 134.3 PICOFARADS.
C           THE PROGRAM WILL GRAPH THE FREQUENCY RESPONSE BETWEEN
C           FL = 50.0 MHZ AND FH = 62.0 MHZ .
C
C           NOTE: FOR THIS CALCULATION THE VELOCITY FACTOR ( VF )
C           OF THE CABLE IS NOT USED BUT STILL SHOULD BE INCLUDED AS
C           INPUT DATA.
C
C
C        ***** NOTE: ENTER THE FOLLOWING VARIABLES IF IOPT = 1 .
C
C
C        XLMIN (D13.6): THE LOWER LIMIT OF THE INDUCTIVE REACTANCE
C           IN OHMS OF THE GENERAL DESIGN GRAPHS.
C
```

```
C     XLMAX (D13.6): THE UPPER LIMIT OF THE INDUCTIVE REACTANCE IN OHMS
C        OF THE GENERAL DESIGN GRAPHS.
C        FOR EACH CIRCUIT THE FOLLOWING GRAPHS WILL BE MADE:
C        XC1 VS. XL BETWEEN XL = XLMIN AND XL = XLMAX, AT FIXED Q, ZIN
C        XC2 VS. XL BETWEEN XL = XLMIN AND XL = XLMAX, AT FIXED Q, ZIN
C        AND/OR
C        D1 VS. XL BETWEEN XL = XLMIN AND XL = XLMAX, AT FIXED Q, ZIN
C        D2 VS. XL BETWEEN XL = XLMIN AND XL = XLMAX, AT FIXED Q, ZIN
C
C        XC1 AND XC2 ARE THE CAPACITIVE REACTANCES OF CAPACITORS
C        C1 AND C2.  D1 AND D2 ARE THE WAVELENGTHS IN FREE SPACE OF
C        CABLES D1 AND D2 .
C
C     Q (D13.6): DEFINED ABOVE.
C        DESIGN GRAPHS WILL BE DRAWN AT FIXED Q.
C
C     ZIN (D13.6): DEFINED ABOVE.
C        PROBES WILL BE TUNED TO AN INPUT IMPEDANCE = ZIN AT 0.0
C        DEGREES PHASE ANGLE AT ANY PARTICULAR FREQUENCY CHOSEN.
C        DESIGN GRAPHS WILL BE DRAWN AT FIXED ZIN .
C
C
C     *****  EXAMPLE:
C
C        USE OF DESIGN GRAPHS AND/OR TABLES:
C
C        SUPPOSE A DESIGN GRAPH FOR A TAPPED SERIES TUNED PROBE WAS
C        MADE BETWEEN XLMIN = 10.0 OHMS AND XLMAX = 500.0 OHMS AT
C        Q = 19.1 AND FOR ZIN = 50.0 OHMS.
C
C        A TYPICAL NMR INDUCTOR MIGHT HAVE XL = 145.0 OHMS
C        AT F0 = 56.0 MHZ.  BY PLACING THIS INDUCTOR IN SERIES WITH
C        AN RL = 7.59 OHM RESISTOR A Q = XL/RL = 19.1 CAN BE
C        REALIZED.   FROM THE DESIGN GRAPHS XC1 = 127.0 OHMS AND
C        XC2 = 21.0 OHMS CAN BE READ.
C        USING THE RELATIONSHIPS:
C        C1 = 1.0/(2*PI*F0*XC1)    AND    C2 = 1.0/(2*PI*F0*XC2)
C        THEN C1 =22.4 PICOFARADS AND C2 = 134.3 PICOFARADS.
C
C        NOTE: DISTANCES D1 AND D2 ARE IN WAVELENGTHS IN FREE SPACE.
C        THESE VALUES SHOULD BE MULTIPLIED BY THE WAVELENGTH IN THE
C        CABLE AT THE PARTICULAR FREQUENCY CHOSEN.
C
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 WTEMP(1200)
      REAL*8 BTEMP(8)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT,XLINC
      COMMON /GHI/ WTEMP
      COMMON /JKL/ IPRINT
      COMMON /MNO/ BTEMP
      BPI=6.283185D0
      XC1=1.0D0
      XC2=1.0D0
      X10=1.0D0
      X20=1.0D0
      D1=1.0D0
```

```
      X100=1.0D0
      D10=1.0D0
      D20=1.0D0
      READ(5,124) IOPT,ICIRC,IPRINT
124   FORMAT(I1)
      IF(IOPT.NE.0.0D0) GO TO 2
      READ(5,4) F0,XL,Q,ZIN,VF,FL,FH
4     FORMAT(D13.6)
      IF(VF.LE.0.0D0.OR.VF.GT.1.0D0) VF=0.66
      RL=FH
      IF(FL.GT.FH) FH=FL
      IF(FH.EQ.FL) FL=RL
      RL=XL/Q
      WRITE(6,14)
14    FORMAT('1',20X,'*****  DESIGN NMR PROBE  *****',/
     $'-',10X,'INPUT DATA FOLLOWS:')
      WRITE(6,24) IOPT,ICIRC,IPRINT
24    FORMAT('-',10X,'PROGRAM OPTION, IOPT = ',I2,8X,'0- SINGLE FREQ. DE
     $SIGN',5X,'1- GENERAL DESIGN',/
     $       '-',10X,'CIRCUIT SELECTOR, ICIRC = ',I2,5X,'1- TAPPED PARAL
     $LEL TUNED',5X,'2- TAPPED SERIES TUNED',/
     $'0',43X,'3- HYBRID TUNED',5X,'4-SHORTED STUB TUNED',5X,
     $'5- ALL FOUR CIRCUITS',/
     $'-',10X,'PRINT CONTROL, IPRINT = ',I2, 7X,'0- GRAPH DATA NCT PRINT
     $ED',5X,'1- ALL GRAPH DATA PRINTED')
      WRITE(6,134) F0,XL,Q,ZIN,VF,FL,FH
134   FORMAT(
     $'-',10X,'RESONANT FREQUENCY, F0 = ',1PD13.6,' MEGAHERTZ',/
     $'0',10X,'INDUCTIVE REACTANCE OF COIL, XL = ',1PD13.6,' OHMS',/
     $'0',10X,'QUALITY FACTOR, Q = ',1PD13.6,5X,'Q = XL/RL',/
     $'0',10X,'INPUT IMPEDANCE OF PROBE, ZIN = ',1PD13.6,' OHMS   AT PHA
     $SE ANGLE = 0.0 DEGREES',/
     $'0',10X,'VELOCITY FACTOR OF CABLE, VF = ',1PD13.6,/
     $'0',10X,'LOWER LIMIT OF FREQUENCY RESPONSE GRAPH, FL = ',1PD13.6,
     $' MEGAHERTZ',/
     $'0',10X,'UPPER LIMIT OF FREQUENCY RESPONSE GRAPH, FH = ',1PD13.6,
     $' MEGAHERTZ')
      IF(RL.GE.ZIN) GO TO 1
      CON1=1.0D6/BPI/F0
      CON2=3.0D4*VF/F0
      IF(ICIRC.LE.1.OR.ICIRC.GT.4)
     $CALL DTPTC(XC1,XC2,ZIN)
      C1TP=CON1/XC1
      C2TP=CON1/XC2
      IF(ICIRC.EQ.2.OR.ICIRC.GT.4)
     $CALL DTSTC(X10,X20,ZIN)
      C1TS=CON1/X10
      C2TS=CON1/X20
      IF(ICIRC.EQ.3.OR.ICIRC.GT.4)
     $CALL DHTC(X100,D1,ZIN)
      D1H=D1*CON2
      C1H=CON1/X100
      IF(ICIRC.GE.4)
     $CALL DSSTC(D10,D20,ZIN)
      D1S=CON2*D10
      D2S=CON2*D20
      TAU=42.0D0*Q/BPI/F0
      WRITE(6,64) RL,TAU
```

```
64      FORMAT('1'.20X.'*****  CALCULATED VALUES FOLLOW :  *****',/
       $'-',10X,'-----  LOAD RESISTOR, RL = ',1PD13.6,' OHMS  -----',/
       $'0',10X,'-----  RINGDOWN TIME, TAU = ',1PD13.6,' MICROSECONDS',
       $5X,'TAU = 21*Q/(PI*F0)  -----')
        IF(ICIRC.LE.1.OR.ICIRC.GT.4)
       $WRITE(6,34) C1TP,C2TP
34      FORMAT('-',20('*'),' TAPPED PARALLEL TUNED CIRCUIT ',20('*'),/
       $'0',10X,'C1= ',1PD13.6,' PICOFARADS'/
       *'0',10X,'C2= ',1PD13.6,' PICOFARADS')
        IF(ICIRC.EQ.2.OR.ICIRC.GT.4)
       $WRITE(6,54) C1TS,C2TS
54      FORMAT('-',20('*'),' TAPPED SERIES TUNED CIRCUIT **',20('*'),/
       $'0',10X,'C1= ',1PD13.6,' PICOFARADS'/
       *'0',10X,'C2= ',1PD13.6,' PICOFARADS')
        IF(ICIRC.EQ.3.OR.ICIRC.GT.4)
       $WRITE(6,74) ZIN,D1H,C1H
74      FORMAT('-',20('*'),' HYBRID TUNED CIRCUIT *********',20('*'),/
       $'0',10('-'),' NOTE: CABLE WITH CHARACTERISTIC IMPEDANCE OF'
       *,1PD13.6,' OHMS MUST BE USED.',/
       $'0',10X,'D1= ',1PD13.6,' CENTIMETERS',/
       *'0',10X,'C1= ',1PD13.6,' PICOFARADS')
        IF(ICIRC.GE.4)
       $WRITE(6,94) ZIN,D1S,D2S
94      FORMAT('-',20('*'),' SHORTED STUB TUNED CIRCUIT ***',20('*'),/
       $'0',10('-'),' NOTE: CABLE WITH CHARACTERISTIC IMPEDANCE OF'
       *,1PD13.6,' OHMS MUST BE USED.',/
       $'0',10X,'D1= ',1PD13.6,' CENTIMETERS',/
       *'0',10X,'D2= ',1PD13.6,' CENTIMETERS')
        HZPT=(FH-FL)/400.0D0
        IF(ICIRC.LE.1.OR.ICIRC.GT.4)
       $CALL TPTC(C1TP,C2TP)
        IF(ICIRC.EQ.2.OR.ICIRC.GT.4)
       $CALL TSTC(C1TS,C2TS)
        IF(ICIRC.EQ.3.OR.ICIRC.GT.4)
       $CALL HT(C1H,D1H,ZIN)
        IF(ICIRC.GE.4)
       $CALL SST(D1S,D2S,ZIN)
        STOP
2       CONTINUE
        READ(5,4) XLMIN,XLMAX,Q,ZIN
        RL=XLMIN
        IF(XLMIN.GT.XLMAX) XLMIN=XLMAX
        IF(XLMIN.EQ.XLMAX) XLMAX=RL
        WRITE(6,14)
        WRITE(6,24) IOPT,ICIRC,IPRINT
        WRITE(6,144) XLNIN,XLMAX,Q,ZIN
144     FORMAT('-',10X,'LOWER LIMIT OF INDUCTIVE REACTANCE GRAPH, XLMIN =
       $',1PD13.6,' OHMS',/
       $'0',10X,'UPPER LIMIT OF INDUCTIVE REACTANCE GRAPH, XLMAX = ',
       $1PD13.6,' OHMS',/
       $'0',10X,'QUALITY FACTOR, Q = ',1PD13.6,/
       $'0',10X,'INPUT IMPEDANCE OF PROBE, ZIN = ',1PD13.6,
       $' OHMS',5X,'AT 0.0 DEGREES PHASE ANGLE')
        RL=XLMAX/Q
        IF(RL.GE.ZIN) GO TO 3
        XLINC=(XLMAX-XLMIN)/400.0D0
        XL=XLMIN-XLINC
        IF(ICIRC.LE.1.OR.ICIRC.GT.4)
```

```
     $CALL DGTPTC(Q,ZIN)
      XL=XLMIN-XLINC
      IF(ICIRC.EQ.2.OR.ICIRC.GT.4)
     $CALL DGTSTC(Q,ZIN)
      XL=XLMIN-XLINC
      IF(ICIRC.EQ.3.OR.ICIRC.GT.4)
     $CALL DGHTC(Q,ZIN)
      XL=XLMIN-XLINC
      IF(ICIRC.GE.4)
     $CALL DGSSTC(Q,ZIN)
      STOP
1     WRITE(6,5) RL,ZIN
5     FORMAT('1',10X,' RL= XL/Q = ',1PD13.6,' OHMS IS > OR = TO',/
     $'0',10X,'ZIN= ',1PD13.6,' OHMS AND TUNING USING THESE CIRCUITS IS
     $ PRACTICALLY OR COMPLETELY IMPOSSIBLE',/
     $'0',10X,'ASSIGN ANOTHER Q WHICH IS ACCEPTABLE')
      STOP
3     WRITE(6,154) XLMAX,RL,ZIN
154   FORMAT('1',10X,'THE UPPER LIMIT OF INDUCTIVE REACTANCE, XLMAX = ',
     $1PD13.6,' OHMS IS TOO LARGE.',/
     $'0',10X,'RL = XLMAX/Q = ',1PD13.6,' OHMS IS > OR = TO ZIN = ',
     $1PD13.6,' OHMS',/
     $'0',10X,'INCREASE THE VALUE OF Q OR DECREASE THE VALUE OF XLMAX')
      STOP
      END
```

```
      SUBROUTINE DTPTC(XC1,XC2,BCAB)
C
C     THIS SUBROUTINE WILL CALCULATE THE CAPACITIVE REACTANCES,
C     XC1 AND XC2, REQUIRED TO TUNE A TAPPED PARALLEL TUNED CIRCUIT
C     TO ZIN = BCAB AT 0.0 DEGREES PHASE ANGLE.
C     XL IS THE INDUCTIVE REACTANCE OF THE COIL AND RL IS THE
C     LOAD RESISTANCE.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON /MNO/ B1,B2,B3
      B1=DSQRT(BCAB*RL*(RL**2+XL**2-BCAB*RL))
      B2=BCAB-RL
      XC1=(BCAB*XL+B1)/B2
      B3=XL-XC1
      B1=RL**2+XL*B3
      B2=RL**2+B3**2
      XC2=-XC1*B1/B2
      RETURN
      END
```

```
      SUBROUTINE DTSTC(X10,X20,BCAB)
C
C     THIS SUBROUTINE WILL CALCULATE THE CAPACITIVE REACTANCES,
C     X10 AND X20, REQUIRED TO TUNE A TAPPED SERIES TUNED CIRCUIT
C     TO ZIN = BCAB AT 0.0 DEGREES PHASE ANGLE.
C     XL IS THE INDUCTIVE REACTANCE OF THE COIL AND RL IS THE
C     LOAD RESISTANCE.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON /MNO/ A601,A60
      EQUIVALENCE(A50,BCAB),(A20,RL),(A10,XL)
       A601=A20*A50-A20**2
      A60=DSQRT(A601)
      X10=A10-A60
      X20=A20*A50/A60
      RETURN
      END
```

```
      SUBROUTINE DHTC(XC1,D1,BCAB)
C
C     THIS SUBROUTINE WILL CALCULATE THE CAPACITIVE REACTANCE, XC1,
C     AND CABLE WAVELENGTH, D1, REQUIRED TO TUNE A HYBRID TUNED CIRCUIT
C     TO ZIN = BCAB AT 0.0 DEGREES PHASE ANGLE.
C     XL IS THE INDUCTIVE REACTANCE OF THE COIL AND RL IS THE
C     LOAD RESISTANCE.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON /MNO/ B3,B2,B1,B4,B0,B5,B6,B7
      B3=BCAB**2-BCAB*RL
      B2=-2.0D0*BCAB*XL
      B1=XL**2+RL**2-BCAB*RL
       B4=B2**2-4.0D0*B1*B3
      B4=-(B2+DSQRT(B4))/2.0D0/B1
      D1=DATAN(B4)/BPI
      IF(D1.LT.0.0D0) D1=D1+0.5
      B0=BCAB*XL
      B1=BCAB**2-XL**2-RL**2
      B2=-XL*BCAB
      B3=DTAN(BPI*D1)
      B4=BCAB-XL*B3
      B5=RL*B3
      B6=B0+B1*B3+B2*B3**2
      B7=B4**2+B5**2
      B6=B6/B7
      XC1=BCAB*B6
      RETURN
      END
```

```
      SUBROUTINE DSSTC(D1.D2,BCAB)
C
C     THIS SUBROUTINE WILL CALCULATE THE CABLE WAVELENGTHS, D1 AND
C     D2, REQUIRED TO TUNE A SHORTED STUB TUNED CIRCUIT
C     TO ZIN = BCAB AT 0.0 DEGREES PHASE ANGLE.
C     XL IS THE INDUCTIVE REACTANCE OF THE COIL AND RL IS THE
C     LOAD RESISTANCE.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0.FL,FH
      COMMON /MNO/ B3,B2,B1,B4,B0,B5,B6,B7
      B1=BCAB*RL-BCAB**2
      B2=-2.0D0*XL*BCAB
      B3=RL*BCAB-RL**2-XL**2
       B4=B2**2-4.0D0*B1*B3
      B4=-(B2-DSQRT(B4))/2.0D0/B1
      D1=DATAN(B4)/BPI
      IF(D1.LT.0.) D1=D1+0.5
      B3=DTAN(BPI*D1)
      B0=-BCAB*XL
      B1=RL**2+XL**2-BCAB**2
      B2=XL*BCAB
      B4=BCAB*B3+XL
      B6=B0+B1*B3+B2*B3**2
      B7=RL**2+B4**2
      B6=B6/B7
      B7=DATAN(1.0D0/B6)/BPI
      IF(B7.LT.0.0D0) B7=B7+0.5
      D2=B7
      RETURN
      END
```

```
      SUBROUTINE TPTC(C1,C2)
C
C     THIS SUBROUTINE WILL CALCULATE THE IMPEDANCE FREQUENCY
C     RESPONSE AND THE PHASE ANGLE FREQUENCY RESPONSE BETWEEN
C     FREQUENCIES, FH AND FL FOR THE TAPPED PARALLLEL TUNED CIRCUIT.
C     THE COIL HAS INDUCTIVE REACTANCE, XL.  RL IS THE LOAD RESISTANCE.
C     C1 AND C2 ARE THE TUNING CAPACITORS IN PICOFARADS.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMPLEX*16 Z10,Z20,Z30,ZIN,DCMPLX
      REAL*8 DREAL,DIMAG,CDABS,DATAN2
      DIMENSION X(400),Y1(400),Y2(400)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT
      COMMON /GHI/ X,Y1,Y2
      COMMON /JKL/ IPRINT
      XC1=CON1/C1
      XC2=CON1/C2
      F20=F0
      F10=FL-HZPT
      DO 10 N=1,400
      F10=F10+HZPT
       B1=F10/F20
      B2=-XC2/B1
      B3=XL*B1-XC1/B1
      B4=-XC1*RL/B1
      B5=XC1*XL
      Z10=DCMPLX(0.0D0,B2)
      Z20=DCMPLX(RL,B3)
      Z30=DCMPLX(B5,B4)
      ZIN=Z10+Z30/Z20
      R=DREAL(ZIN)
      A=DIMAG(ZIN)
      A=57.29578D0*DATAN2(A,R)
       R=CDABS(ZIN)
      Y1(N)=R
      Y2(N)=A
      X(N)=F10
10    CONTINUE
      NUM=-400
      CALL GRAPH(NUM,X,Y1,11,2,12.,9.,0.,0.,0.,0.,
     $'FREQ ( MHZ )        ','ZIN ( OHMS )        ',
     $'ZIN VS. FREQ        ','TAPPED PARALLEL     ')
      CALL GRAPH(NUM,X,Y2,11,2,12.,9.,0.,0.,0.,0.,
     $'FREQ ( MHZ )        ','PHASE ANGLE ( DEG ) ',
     $'PHASE ANGLE VS. FREQ','TAPPED PARALLEL     ')
      IF(IPRINT.NE.1) RETURN
      NUM=400
      WRITE(6,4)
4     FORMAT('1',10X,'FREQUENCY RESPONSE OF TAPPED PARALLEL TUNED CIRCUI
     $T FOLLOWS:',/
     $'-',T4,'FREQ( MHZ )',T24,'ZIN( OHMS )',T40,'PHASE ANGLE( DEG )',
     $T64,'FREQ( MHZ )',T84,'ZIN( OHMS )',T100,'PHASE ANGLE( DEG )',//)
      DO 11 I=1,NUM,2
      WRITE(6,14) X(I),Y1(I),Y2(I),X(I+1),Y1(I+1),Y2(I+1)
14    FORMAT(' ',6(1PD13.6,7X))
11    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TSTC(C10,C20)
C
C     THIS SUBROUTINE WILL CALCULATE THE IMPEDANCE FREQUENCY
C     RESPONSE AND THE PHASE ANGLE FREQUENCY RESPONSE BETWEEN
C     FREQUENCIES, FH AND FL FOR THE TAPPED SERIES TUNED CIRCUIT.
C     THE COIL HAS INDUCTIVE REACTANCE, XL.  RL IS THE LOAD RESISTANCE.
C     C10 AND C20 ARE THE TUNING CAPACITORS IN PICOFARADS.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMPLEX*16 Z10,Z20,Z30,Z40,Z50,DCMPLX
      REAL*8 DREAL,DIMAG,CDABS,DATAN2
      REAL*8 X(400),YX1(400),YX2(400)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT
      COMMON /GHI/ X,YX1,YX2
      COMMON /JKL/ IPRINT
      Z40=DCMPLX(1.0D0,0.0D0)
       F10=FL-HZPT
      DO 10 I=1,400
      F10=F10+HZPT
      XL1=XL*F10/F0
      XC1=CON1/C10*(F0/F10)
      XC2=CON1/C20*(F0/F10)
      XC3=XL1-XC1
      Z10=DCMPLX(RL,XC3)
      Z20=DCMPLX(0.0D0,-XC2)
      Z50=Z40/Z20+Z40/Z10
      Z30=Z40/Z50
      R1=CDABS(Z30)
      R2=DREAL(Z30)
      A1=DIMAG(Z30)
      A2=DATAN2(A1,R2)*57.29578D0
      X(I)-F10
      YX1(I)=R1
      YX2(I)=A2
10     CONTINUE
      NUM=-400
      CALL GRAPH(NUM,X,YX1,11,2,12.,9.,0.,0.,0.,0.,
     $'FREQ ( MHZ )          ','ZIN ( OHMS )          ',
     $'ZIN VS. FREQ          ','TAPPED SERIES         ')
      CALL GRAPH(NUM,X,YX2,11,2,12.,9.,0.,0.,0.,0.,
     $'FREQ ( MHZ )          ','PHASE ANGLE ( DEG ) ',
     $'PHASE ANGLE VS. FREQ','TAPPED SERIES         ')
      IF(IPRINT.NE.1) RETURN
      NUM=400
      WRITE(6,4)
4     FORMAT('1',10X,'FREQUENCY RESPONSE OF TAPPED SERIES TUNED CIRCUIT
     $FOLLOWS:',/
     $'-',T4,'FREQ( MHZ )',T24,'ZIN( OHMS )',T40,'PHASE ANGLE( DEG )',
     $T64,'FREQ( MHZ )',T84,'ZIN( OHMS )',T100,'PHASE ANGLE( DEG )',//)
      DO 11 I=1,NUM,2
      WRITE(6,14) X(I),YX1(I),YX2(I),X(I+1),YX1(I+1),YX2(I+1)
14    FORMAT(' ',6(1PD13.6,7X))
11    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE HT(C1,D1,ZIN)
C
C     THIS SUBROUTINE WILL CALCULATE THE IMPEDANCE FREQUENCY
C     RESPONSE AND THE PHASE ANGLE FREQUENCY RESPONSE BETWEEN
C     FREQUENCIES, FH AND FL FOR THE HYBRID TUNED CIRCUIT.
C     THE COIL HAS INDUCTIVE REACTANCE, XL.  RL IS THE LOAD RESISTANCE.
C     C1 IS THE TUNING CAPACITOR IN PICOFARADS AND D1 IS THE TUNING
C     CABLE LENGTH IN CENTIMETERS.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMPLEX*16 Z10,Z20,Z30,Z40,Z90,DCMPLX,CDEXP
      REAL*8 X(400),Y1(400),Y2(400)
      REAL*8 DREAL,DIMAG,CDABS,DATAN2
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT
      COMMON /GHI/ X,Y1,Y2
      COMMON /JKL/ IPRINT
      AT=0.0D0
      R10=RL
      XC1=CON1/C1
      D=D1/CON2
      F20=F0
      Z40=DCMPLX(ZIN,0.0D0)
      F10=FL-HZPT
      DO 10 I=1,400
      F10=F10+HZPT
      A10=XL*F10/F20
      Z30=DCMPLX(R10,A10)
      C21=BPI*F10/F20
      Z90=DCMPLX(AT,C21)
      Z10=CDEXP(-2.0D0*Z90*D)
      Z20=(Z30*(1.-Z10)+Z40*(1.+Z10))/(Z30*(1.+Z10)+Z40*(1.-Z10))
      Z20=Z40/Z20
      R20=DREAL(Z20)
      A20=DIMAG(Z20)
      B1=XC1*F20/F10
      A20=A20-B1
      Z20=DCMPLX(R20,A20)
      R20=DREAL(Z20)
      A20=DIMAG(Z20)
      A20=57.29578D0*DATAN2(A20,R20)
      R20=CDABS(Z20)
      X(I)=F10
      Y1(I)=R20
      Y2(I)=A20
10    CONTINUE
      NUM=-400
      CALL GRAPH(NUM,X,Y1,11,2,12.,9.,0.,0.,0.,0.,
     $'FREQ ( MHZ )        ','ZIN ( OHMS )        ',
     $'ZIN VS. FREQ        ','HYBRID TUNED        ')
      CALL GRAPH(NUM,X,Y2,11,2,12.,9.,0.,0.,0.,0.,
     $'FREQ ( MHZ )        ','PHASE ANGLE ( DEG ) ',
     $'PHASE ANGLE VS. FREQ','HYBRID TUNED        ')
      IF(IPRINT.NE.1) RETURN
      NUM=400
```

```
      WRITE(6,4)
4     FORMAT('1',10X,'FREQUENCY RESPONSE OF HYBRID TUNED CIRCUIT FOLLOWS
     $:',/
     $'-',T4,'FREQ( MHZ )',T24,'ZIN( OHMS )',T40,'PHASE ANGLE( DEG )',
     $T64,'FREQ( MHZ )',T84,'ZIN( OHMS )',T100,'PHASE ANGLE( DEG )',//)
      DO 11 I=1,NUM,2
      WRITE(6,14) X(I),Y1(I),Y2(I),X(I+1),Y1(I+1),Y2(I+1)
14    FORMAT(' ',6(1PD13.6,7X))
11    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SST(DA,DB,ZIN)
C
C     THIS SUBROUTINE WILL CALCULATE THE IMPEDANCE FREQUENCY
C     RESPONSE AND THE PHASE ANGLE FREQUENCY RESPONSE BETWEEN
C     FREQUENCIES, FH AND FL FOR THE SHORTED STUB TUNED CIRCUIT.
C     THE COIL HAS INDUCTIVE REACTANCE, XL.  RL IS THE LOAD RESISTANCE.
C     DA AND DB ARE THE TUNING CABLE LENGTHS IN CENTIMETERS.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMPLEX*16 Z10,Z20,Z30,Z40,Z90,DCMPLX,CDEXP
      REAL*8 X(400),Y1(400),Y2(400)
      REAL*8 DREAL,DIMAG,CDABS,DATAN2
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT
      COMMON /GHI/ X,Y1,Y2
      COMMON /JKL/ IPRINT
      AI=0.0D0
      R10=RL
      D=DA/CON2
      D1=DB/CON2
      F20=F0
      Z40=DCMPLX(ZIN,0.0D0)
      F10=FL-HZPT
      DO 10 I=1,400
      F10=F10+HZPT
      A10=XL*F10/F20
      Z30=DCMPLX(R10,A10)
      C21=BPI*F10/F20
      Z90=DCMPLX(AT,C21)
```

```
      Z10=CDEXP(-2.0D0*Z90*D)
      Z20=(Z30*(1.-Z10)+Z40*(1.+Z10))/(Z30*(1.+Z10)+Z40*(1.-Z10))
      R20=DREAL(Z20)
      A20=DIMAG(Z20)
      A20=A20-DCOTAN(C21*D1)
      Z20=DCMPLX(R20,A20)
      Z20=Z40/Z20
      R20=DREAL(Z20)
      A20=DIMAG(Z20)
      A20=57.29578D0*DATAN2(A20,R20)
      R20=CDABS(Z20)
      X(I)=F10
      Y1(I)=R20
      Y2(I)=A20
10    CONTINUE
      NUM=-400
      CALL GRAPH(NUM,X,Y1,11,2,12.,9.,0.,0.,0.,0.,
     $'FREQ ( MHZ )          ','ZIN ( OHMS )          ',
     $'ZIN VS. FREQ          ','SHORTED STUB          ')
      CALL GRAPH(NUM,X,Y2,11,2,12.,9.,0.,0.,0.,0.,
     $'FREQ ( MHZ )          ','PHASE ANGLE ( DEG ) ',
     $'PHASE ANGLE VS. FREQ','SHORTED STUB          ')
      IF(IPRINT.NE.1) RETURN
      NUM=400
      WRITE(6,4)
4     FORMAT('1',10X,'FREQUENCY RESPONSE OF SHORTED STUB TUNED CIRCUIT F
     $OLLOWS:',/
     $'-',T4,'FREQ( MHZ )',T24,'ZIN( OHMS )',T40,'PHASE ANGLE( DEG )',
     $T64,'FREQ( MHZ )',T84,'ZIN( OHMS )',T100,'PHASE ANGLE( DEG )',//)
      DO 11 I=1,NUM,2
      WRITE(6,14) X(I),Y1(I),Y2(I),X(I+1),Y1(I+1),Y2(I+1)
14    FORMAT(' ',6(1PD13.6,7X))
11    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DGTPTC(Q,ZIN)
C
C     THIS SUBROUTINE WILL CALCULATE THE GENERAL DESIGN GRAPHS
C     AT FIXED Q AND FIXED INPUT IMPEDANCE, ZIN AT 0.0 DEGREES PHASE
C     ANGLE, BETWEEN INDUCTIVE REACTANCES XLMIN AND XLMAX.
C     THE DESIGN GRAPHS ARE FOR THE TAPPED PARALLEL TUNED CIRCUIT.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 X(400),Y1(400),Y2(400)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT,XLINC
      COMMON /GHI/ X,Y1,Y2
      COMMON /JKL/ IPRINT
      DO 10 I=1,400
      XL=XL+XLINC
      RL=XL/Q
      CALL DTPTC(XC1,XC2,ZIN)
      X(I)=DLOG10(XL)
      Y1(I)=DLOG10(XC1)
      Y2(I)=DLOG10(XC2)
10    CONTINUE
      NUM=-400
      CALL GRAPH(NUM,X,Y1,11,2,-12.,-9.,0.,0.,0.,0.,
     $'XL ( OHMS )            ','XC1 ( OHMS )            ',
     $'XC1 VS. XL ( LOG10 )','TAPPED PARALLEL      ')
      CALL GRAPH(NUM,X,Y2,11,2,-12.,-9.,0.,0.,0.,0.,
     $'XL ( OHMS )            ','XC2 ( OHMS )            ',
     $'XC2 VS. XL ( LOG10 )','TAPPED PARALLEL      ')
      IF(IPRINT.NE.1) RETURN
      NUM=400
      WRITE(6,4)
4     FORMAT('1',10X,'DESIGN VALUES FOR TAPPED PARALLEL TUNED CIRCUIT FO
     $LLOW:',/
     $'-',T4,'XL( OHMS )',T24,'XC1( OHMS )',T44,'XC2( OHMS )',
     $T64,'XL( OHMS )',T84,'XC1( OHMS )',T104,'XC2( OHMS )',//)
      DO 11 I=1,NUM,2
      X(I)=10**X(I)
      Y1(I)=10**Y1(I)
      Y2(I)=10**Y2(I)
      X(I+1)=10**X(I+1)
      Y1(I+1)=10**Y1(I+1)
      Y2(I+1)=10**Y2(I+1)
      WRITE(6,14) X(I),Y1(I),Y2(I),X(I+1),Y1(I+1),Y2(I+1)
14    FORMAT(' ',6(1PD13.6,7X))
11    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DGTSTC(Q,ZIN)
C
C     THIS SUBROUTINE WILL CALCULATE THE GENERAL DESIGN GRAPHS
C     AT FIXED Q AND FIXED INPUT IMPEDANCE, ZIN AT 0.0 DEGREES PHASE
C     ANGLE, BETWEEN INDUCTIVE REACTANCES XLMIN AND XLMAX.
C     THE DESIGN GRAPHS ARE FOR THE TAPPED SERIES TUNED CIRCUIT.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 X(400),Y1(400),Y2(400)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT,XLINC
      COMMON /GHI/ X,Y1,Y2
      COMMON /JKL/ IPRINT
      DO 10 I=1,400
      XL=XL+XLINC
      RL=XL/Q
      CALL DTSTC(XC1,XC2,ZIN)
      X(I)=DLOG10(XL)
      Y1(I)=DLOG10(XC1)
      Y2(I)=DLOG10(XC2)
10    CONTINUE
      NUM=-400
      CALL GRAPH(NUM,X,Y1,11,2,-12.,-9.,0.,0.,0.,0.,
     $'XL ( OHMS )          ','XC1 ( OHMS )          ',
     $'XC1 VS. XL ( LOG10 )','TAPPED SERIES         ')
      CALL GRAPH(NUM,X,Y2,11,2,-12.,-9.,0.,0.,0.,0.,
     $'XL ( OHMS )          ','XC2 ( OHMS )          ',
     $'XC2 VS. XL ( LOG10) ','TAPPED SERIES         ')
      IF(IPRINT.NE.1) RETURN
      NUM=400
      WRITE(6,4)
4     FORMAT('1',10X,'DESIGN VALUES FOR TAPPED SERIES TUNED CIRCUIT FOLL
     $OW:',/
     $'-',T4,'XL( OHMS )',T24,'XC1( OHMS )',T44,'XC2( OHMS )',
     $T64,'XL( OHMS )',T84,'XC1( OHMS )',T104,'XC2( OHMS )',//)
      DO 11 I=1,NUM,2
      X(I)=10**X(I)
      Y1(I)=10**Y1(I)
      Y2(I)=10**Y2(I)
      X(I+1)=10**X(I+1)
      Y1(I+1)=10**Y1(I+1)
      Y2(I+1)=10**Y2(I+1)
      WRITE(6,14) X(I),Y1(I),Y2(I),X(I+1),Y1(I+1),Y2(I+1)
14    FORMAT(' ',6(1PD13.6,7X))
11    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DGHTC(Q,ZIN)
C
C     THIS SUBROUTINE WILL CALCULATE THE GENERAL DESIGN GRAPHS
C     AT FIXED Q AND FIXED INPUT IMPEDANCE, ZIN AT 0.0 DEGREES PHASE
C     ANGLE, BETWEEN INDUCTIVE REACTANCES XLMIN AND XLMAX.
C     THE DESIGN GRAPHS ARE FOR THE HYBRID TUNED CIRCUIT.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 X(400),Y1(400),Y2(400)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT,XLINC
      COMMON /GHI/ X,Y1,Y2
      COMMON /JKL/ IPRINT
      DO 10 I=1,400
      XL=XL+XLINC
      RL=XL/Q
      CALL DHTC(X100,D1,ZIN)
      X(I)=DLOG10(XL)
      Y1(I)=DLOG10(X100)
      Y2(I)=DLOG10(D1)
10    CONTINUE
      NUM=-400
      CALL GRAPH(NUM,X,Y1,11,2,-12.,-9.,0.,0.,0.,0.,
     $'XL ( OHMS )            ','XC1 ( OHMS )            ',
     $'XC1 VS. XL ( LOG10 )','HYBRID TUNED            ')
      CALL GRAPH(NUM,X,Y2,11,2,-12.,-9.,0.,0.,0.,0.,
     $'XL ( OHMS )            ','D1 ( WAVELENGTHS )  ',
     $'D1 VS. XL ( LOG10 ) ','HYBRID TUNED            ')
      IF(IPRINT.NE.1) RETURN
      NUM=400
      WRITE(6,4)
4     FORMAT('1',10X,'DESIGN VALUES FOR HYBRID TUNED CIRCUIT FOLLOW:',/
     $'-',T4,'XL( OHMS )',T24,'XC1( OHMS )',T42,'D1( WVELNGTHS )',
     $T64,'XL( OHMS )',T84,'XC1( OHMS )',T102,'D1( WVELNGTHS )',//)
      DO 11 I=1,NUM,2
      X(I)=10**X(I)
      Y1(I)=10**Y1(I)
      Y2(I)=10**Y2(I)
      X(I+1)=10**X(I+1)
      Y1(I+1)=10**Y1(I+1)
      Y2(I+1)=10**Y2(I+1)
      WRITE(6,14) X(I),Y1(I),Y2(I),X(I+1),Y1(I+1),Y2(I+1)
14    FORMAT(' ',6(1PD13.6,7X))
11    CONTINUE
      RETURN
      END
```

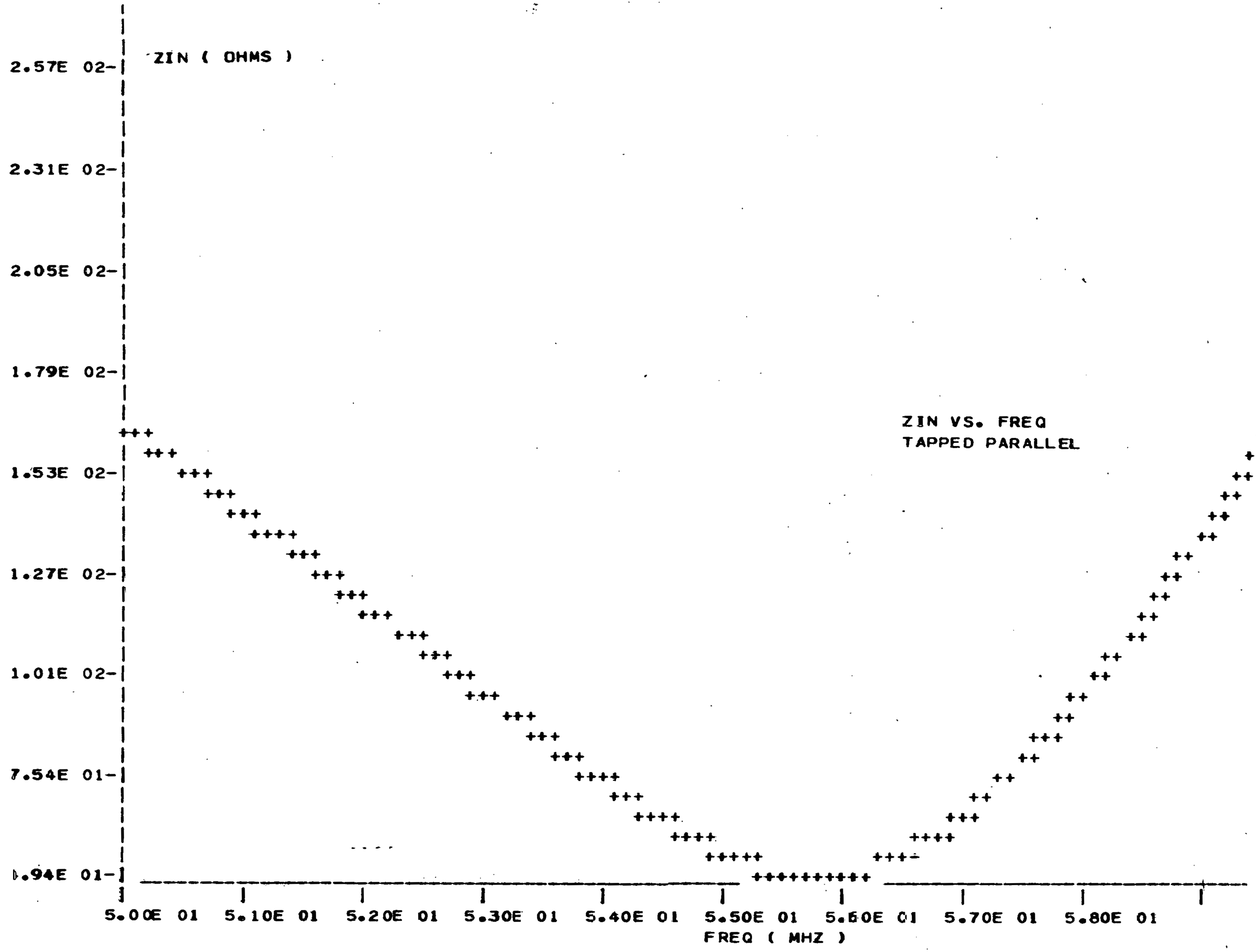
```
      SUBROUTINE DGSSTC(Q,ZIN)
C
C     THIS SUBROUTINE WILL CALCULATE THE GENERAL DESIGN GRAPHS
C     AT FIXED Q AND FIXED INPUT IMPEDANCE, ZIN AT 0.0 DEGREES PHASE
C     ANGLE, BETWEEN INDUCTIVE REACTANCES XLMIN AND XLMAX.
C     THE DESIGN GRAPHS ARE FOR THE SHORTED STUB TUNED CIRCUIT.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 X(400),Y1(400),Y2(400)
      COMMON /ABC/ BPI,CON1,CON2,XL,RL,F0,FL,FH
      COMMON/DEF/ HZPT,XLINC
      COMMON /GHI/ X,Y1,Y2
      COMMON /JKL/ IPRINT
      DO 10 I=1,400
      XL=XL+XLINC
      RL=XL/Q
      CALL DSSTC(D10,D20,ZIN)
      X(I)=DLOG10(XL)
      Y1(I)=DLOG10(D10)
      Y2(I)=DLOG10(D20)
10    CONTINUE
      NUM=-400
      CALL GRAPH(NUM,X,Y1,11,2,-12.,-9.,0.,0.,0.,0.,
     $'XL ( OHMS )             ','D1 ( WAVELENGTHS )  ',
     $'D1 VS. XL ( LOG10 ) ','SHORTED STUB             ')
      CALL GRAPH(NUM,X,Y2,11,2,-12.,-9.,0.,0.,0.,0.,
     $'XL ( OHMS )             ','D2 ( WAVELENGTHS )  ',
     $'D2 VS. XL ( LOG10 ) ','SHORTED STUB             ')
      IF(IPRINT.NE.1) RETURN
      NUM=400
      WRITE(6,4)
4     FORMAT('1',10X,'DESIGN VALUES FOR SHORTED STUB TUNED CIRCUIT FOLLO
     $W:',/
     $'-',T4,'XL( OHMS )',T22,'D1( WVELNGTHS )',T42,'D2( WVELNGTHS )',
     $T64,'XL( OHMS )',T82,'D1( WVELNGTHS )',T102,'D2( WVELNGHTS )',//)
      DO 11 I=1,NUM,2
      X(I)=10**X(I)
      Y1(I)=10**Y1(I)
      Y2(I)=10**Y2(I)
      X(I+1)=10**X(I+1)
      Y1(I+1)=10**Y1(I+1)
      Y2(I+1)=10**Y2(I+1)
      WRITE(6,14) X(I),Y1(I),Y2(I),X(I+1),Y1(I+1),Y2(I+1)
14    FORMAT(' ',6(1PD13.6,7X))
11    CONTINUE
      RETURN
      END
```

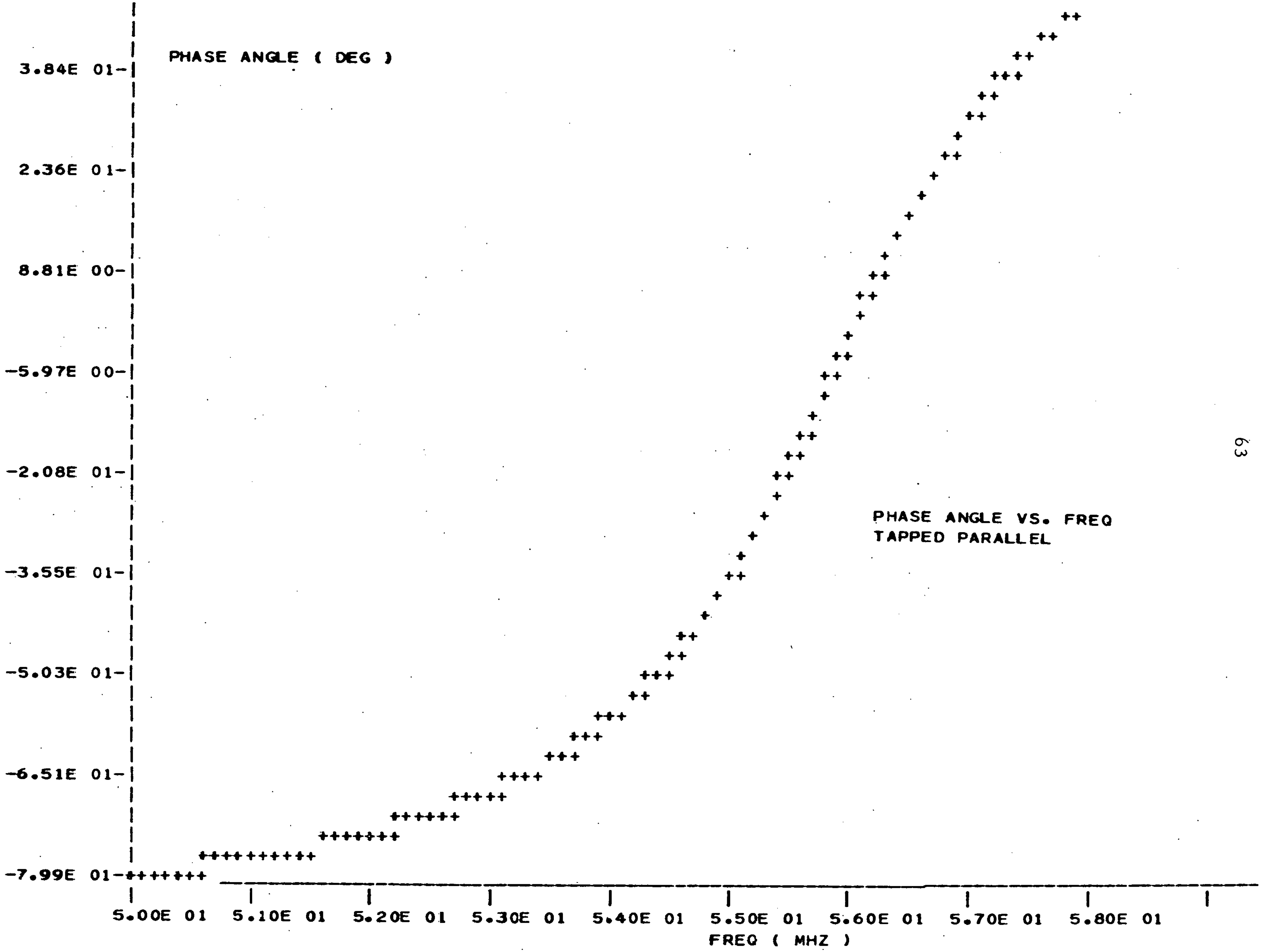
```
      SUBROUTINE  GRAPH(NPTS,X,Y,IDUM1,IDUM2,XDUM1,XDUM2,XDUM3,
     $XDUM4,XDUM5,XDUM6,XLAB,YLAB,GLAB,DATLAB)
C
C     THIS SUBROUTINE WILL GRAPH THE FIRST NPTS ORDERED PAIRS OF
C     POINTS( X(I),Y(I) ) WHICH ARE STORED IN THE ARRAYS X AND Y .
C     A ONE PAGE PRINTER GRAPH OF STANDARD SIZE ( 60 LINES,132 COLUMNS )
C     IS DRAWN . X(I) VALUES CORRESPOND TO THE HORIZONTAL AXES AND
C     Y(I) VALUES CORRESPOND TO THE VERTICAL AXIS .  XLAB AND YLAB
C     ARE THE RESPECTIVES AXES LABELS .  GLAB AND DATLAB ARE GENERAL
C     GRAPH LABELS .  ALL LABELS MUST BE 20 CHARACTERS INCLUDING BLANKS.
C     THE PARAMETERS IDUM1 THROUGH XDUM6 ARE NOT USED .
C     THIS SUBROUTINE WILL PRODUCE A PRINTER GRAPH SIMILAR TO THAT
C     PRODUCED BY THE ISU PLOTTING PACKAGE, SIMPLOTTER .
C     THE STRUCTURE OF THE PARAMETERS IS SUCH THAT THIS SUBROUTINE
C     IS COMPATIBLE FOR USE IN PROGRAMS WHICH WOULD NORMALLY
C     USE SIMPLOTTER .
C
      REAL*8 X(1),Y(1)
      REAL*4 XLAB(5),YLAB(5),GLAB(5),DATLAB(5),XVAL(12)
      INTEGER*2  GRID(61,54),IXGRID,IYGRID,IBLANK,IBAR,ISEVEN,ISODD
      INTEGER*2 IND,ISLSH,IBOTH
      LOGICAL SETEVE,SETODD
      DATA IBLANK/'  '/,IBAR/'__'/,ISEVEN/' +'/,ISODD/'+ '/
      DATA ISLSH/'| '/,IBOTH/'++'/
      NPTS=IABS(NPTS)
      DO 5 I=1,54
      DO 5 J=1,61
      GRID(J,I)=IBLANK
5     CONTINUE
      DO 6 I=1,61
      GRID(I,1)=IBAR
6     CONTINUE
      DO 7 I=1,54
      GRID(1,I)=ISLSH
7     CONTINUE
      XMIN=X(1)
      XMAX=X(1)
      YMIN=Y(1)
      YMAX=Y(1)
      DO 1 I=1,NPTS
      IF(X(I).LT.XMIN) XMIN=X(I)
      IF(Y(I).LT.YMIN) YMIN=Y(I)
      IF(X(I).GT.XMAX) XMAX=X(I)
      IF(Y(I).GT.YMAX) YMAX=Y(I)
1     CONTINUE
      YDIST=YMAX-YMIN
      XDIST=XMAX-XMIN
      XSF=120.0/XDIST
      YSF=50.0/YDIST
      YINC=YDIST/10.0
      XINC=XDIST/12.0
      DO 2 I=1,NPTS
      IYGRID=(Y(I)-YMIN)*YSF+0.5
      IYGRID=IYGRID+1
      IXGRID=(X(I)-XMIN)*XSF+0.5
```

```
      IXGRID=IXGRID+1
      ITEMP=IXGRID
      ISIDE=MOD(ITEMP,2)
      IND=ISEVEN
      IF(ISIDE.NE.0) IND=ISODD
      IXGRID=(IXGRID-1)/2+1
      SETEVE=.FALSE.
      SETODD=.FALSE.
      IF(IND.EQ.ISEVEN) SETEVE=.TRUE.
      IF(IND.EQ.ISODD) SETODD=.TRUE.
      IF(GRID(IXGRID,IYGRID).EQ.IBOTH) IND=IBOTH
      IF(GRID(IXGRID,IYGRID).EQ.ISODD.AND.SETEVE) IND=IBOTH
      IF(GRID(IXGRID,IYGRID).EQ.ISEVEN.AND.SETODD) IND=IBOTH
      GRID(IXGRID,IYGRID)=IND
2     CONTINUE
      WRITE(6,34) GLAB
34    FORMAT('1',T91,5A4)
      WRITE(6,44) DATLAB
44    FORMAT(' ',T91,5A4)
      WRITE(6,4) YLAB
4     FORMAT(' ',5A4)
      DO 3 J=1,54
      IREV=55-J
      ITEMP=IREV-1
      ISIDE=MOD(ITEMP,5)
      YVAL=YMIN+(ITEMP/5)*YINC
      IF(ISIDE.NE.0)
     $WRITE(6,14) (GRID(I,IREV),I=1,61)
14    FORMAT(' ',10X,61A2)
      IF(ISIDE.EQ.0)
     $WRITE(6,54) YVAL,(GRID(I,IREV),I=1,61)
54    FORMAT(' ',1PE9.2,'-',61A2)
3     CONTINUE
      DO 9 I=6,56,5
      GRID(I,54)=ISLSH
9     CONTINUE
      WRITE(6,14) (GRID(I,54),I=1,61)
      DO 8 I=1,12
      XVAL(I)=XMIN+FLOAT(I-1)*XINC
8     CONTINUE
      WRITE(6,74) (XVAL(I),I=1,12)
74    FORMAT(' ',8X,12(1PE9.2,1X))
      WRITE(6,24) XLAB
24    FORMAT(' ',T61,5A4)
      RETURN
      END
```

```
          *****  DESIGN NMR PROBE  *****


INPUT DATA FOLLOWS:


PROGRAM OPTION, IOPT =  0          0- SINGLE FREQ. DESIGN     1- GENERAL DESIGN

CIRCUIT SELECTOR, ICIRC =  5       1- TAPPED PARALLEL TUNED     2- TAPPED SERIES TUNED

                                   3- HYBRID TUNED     4-SHORTED STUB TUNED     5- ALL FOUR CIRCUITS


PRINT CONTROL, IPRINT =  0         0- GRAPH DATA NOT PRINTED     1- ALL GRAPH DATA PRINTED


RESONANT FREQUENCY, F0 =  5.600000D 01 MEGAHERTZ

INDUCTIVE REACTANCE OF COIL, XL =  1.480000D 02 OHMS

QUALITY FACTOR, Q =  1.910000D 01     Q = XL/RL

INPUT IMPEDANCE OF PROBE, ZIN =  5.000000D 01 OHMS   AT PHASE ANGLE = 0.0 DEGREES

VELOCITY FACTOR OF CABLE, VF =  5.600000D-01

LOWER LIMIT OF FREQUENCY RESPONSE GRAPH, FL =  5.000000D 01 MEGAHERTZ

UPPER LIMIT OF FREQUENCY RESPONSE GRAPH, FH =  6.200000D 01 MEGAHERTZ
```

```
                *****  CALCULATED VALUES FOLLOW :  *****

         -----  LOAD RESISTOR, RL =  7.748691D 00 OHMS  -----

         -----  RINGDOWN TIME, TAU =  2.279895D 00 MICROSECONDS     TAU = 21*Q/(PI*F0)  -----

******************** TAPPED PARALLEL TUNED CIRCUIT ********************

         C1=  1.166817D 01 PICOFARADS

         C2=  7.616750D 00 PICOFARADS

******************** TAPPED SERIES TUNED CIRCUIT **********************

         C1=  2.187776D 01 PICOFARADS

         C2=  1.327297D 02 PICOFARADS

******************** HYBRID TUNED CIRCUIT ******************************

---------- NOTE: CABLE WITH CHARACTERISTIC IMPEDANCE OF 5.000000D 01 OHMS MUST BE USED.

         D1=  1.124622D 01 CENTIMETERS

         C1=  7.269195D 00 PICOFARADS

******************** SHORTED STUB TUNED CIRCUIT ***********************

---------- NOTE: CABLE WITH CHARACTERISTIC IMPEDANCE OF 5.000000D 01 OHMS MUST BE USED.

         D1=  9.963907D 01 CENTIMETERS

         D2=  7.157660D 00 CENTIMETERS
```


ZIN (OHMS)
2.57E 02
2.31E 02
2.05E 02
1.79E 02
1.53E 02
1.27E 02
1.01E 02
7.54E 01
4.94E 01
5.00E 01
5.10E 01
5.20E 01
5.30E 01
5.40E 01
5.50E 01
5.60E 01
5.70E 01
5.80E 01
FREQ (MHZ)
ZIN VS. FREQ
TAPPED PARALLEL


PHASE ANGLE VS. FREQ
TAPPED PARALLEL

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