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SINGLE STRAND MODEL COMPUTER PROGRAMS FOR THE TRANSMISSION LINE PROPERTIES OF THE MOORING LINE DATA LINE

D. R. Holt and N. S. Nahman

Electromagnetics Division
Institute for Basic Standards
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Final Report

Prepared for
National Data Buoy Project
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U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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ABSTRACT

Equations and computer programs are presented for calculating the propagation properties of the Mooring Line Data Line (MLDL). The development is based upon a single-strand inner conductor model for the MLDL structure. Propagation parameters, input impedance, voltage amplitude, and current are developed from the complex impedance/meter (Z) and the complex admittance/meter (Y) of the MLDL. A matrix formulation of the voltages and currents along an MLDL loaded with couplers at arbitrary positions is developed. The received voltage and current at the water surface produced by a single coupler down line at an arbitrary distance is presented.

Key Words: attenuation; characteristic impedance; circuit model; computer program; computer printout; coupler; current; impedance; load impedance; mooring line data line; phase; propagation characteristics; sea water return; series impedance; shunt admittance; single strand; transmission line

CHAPTER 1

INTRODUCTION

The objective of the work reported here was to develop computer programs for calculating the propagation properties of the Mooring Line Data Line (MLDL). The programs were based upon a single-strand (inner conductor) model for the MLDL structure. This report is divided into five chapters as described below.

Chapter 1 is the present introduction, and Chapter 2 presents the equations and computer program for calculating the MLDL transmission line parameters Z and Y, the complex impedance/meter and the complex admittance/meter, respectively. Given the MLDL dimensions and material parameters, the complex Z and Y values can be computed for any frequency of interest.

Chapter 3 presents the equations and computer programs for calculating (1) the propagation parameters: α, attenuation (dB/m); B, phase (radians/m); and $\lambda/4$, quarter-wavelength (meters), (2) the MLDL input impedance, (3) the amplitude of the MLDL input voltage, and (4) the current along the MLDL as a function of distance from the sending end. (2), (3), and (4) are computed for the MLDL distant end terminated in a short circuit. Given Z and Y, (1) through (4) can be computed for any frequency of interest.

Chapter 4 presents a matrix formulation of the voltages and currents along an MLDL loaded with couplers at arbitrary positions. A computer program is presented for calculating the current at each coupler. Given Z, Y, the positions of the couplers, and the coupler impedance Z_c, the complex current at each coupler position can be computed for any frequency of interest.

Chapter 5 presents equations and computer programs for calculating the received voltage and current at the water surface produced by a single coupler placed at an arbitrary position along the MLDL (the MLDL is loaded with only one coupler). Given Z, Y, Z_c and the coupler position, the complex voltages and currents produced at the water surface terminals can be computed for any frequency of interest.

CHAPTER 2

MLDL PARAMETER CALCULATIONS

In this chapter, given the MLDL material parameters, the series impedance/m Z and the shunt admittance/m Y are calculated in terms of the single strand model.

The equivalent circuit per unit length of the MLDL is shown in Fig. 2.1 in which s is the complex frequency variable, L is the external inductance, C is the capacitance, $z_1(s)$ is the inner conductor impedance, and $z_2(s)$ is the outer conductor (sea water return) impedance. The line parameters have the definitions †

$$L = \frac{\mu}{2\pi} \ln \frac{r_o}{r_i} \quad \text{(henrys/meter)}, \qquad (2.1)$$

$$C = 2\pi\epsilon \left\{ \ln\left(\frac{r_o}{r_i}\right) \right\}^{-1} \quad \text{(farads/meter)}, \qquad (2.2)$$

$$z_1(s) = R \text{ (ohms/meter)}, \qquad (2.3)$$

$$z_2(s) = \frac{\mu s}{4\pi} \{ \ln \zeta \eta_o s + \gamma_o \} \text{(ohms/meter)}, \qquad (2.4)$$

---

† Definitions (2.1), (2.2), and (2.3) are given in [1].

The impedance expression (2.4) is easily derived from considerin the low frequency expansion of the sea water return expression

$$z_2(s) = \frac{1}{2\pi r_o} \sqrt{\frac{\mu}{\sigma_2}} \frac{K_o(\sqrt{\mu\sigma_2}\, r_o\, s^{1/2})}{K_1(\sqrt{\mu\sigma_2}\, r_o\, s^{1/2})}$$ where K_o, K_1, are modified Bessel functions of second kind [2, 3].

where r_o and r_i denote radii of outer and inner conductors, respectively. The parameter η_o in (2.4) has the definition

$$\eta_o = \frac{\mu}{4}\sigma_2 r_o^2 \quad (\sigma_2,\ \text{conductivity of sea water})$$

where γ_o is Euler's constant, and $\zeta = \epsilon^{\gamma_o}$.

The computer program ZY calculates the series impedance Z and the shunt admittance Y for the circuit model above. As an example consider an isolated single strand of low resistance cable with the dimensions and material parameters shown in Fig. 2.2. The cable has 16 strands of number 28 AWG helically wound on a nylon core, from which we conclude the center conductor impedance is $z_1(s) = 5\ \Omega/1000$ ft.

A sample output for f = 1 KHz and f = 7.2 KHz appears below.

```
                 SINGLE STRAND LINE PARAMETERS
     SERIES IMPEDANCE AND SHUNT ADMITTANCE CALCULATIONS
                        IN MKS UNITS




            Z                          Y                     F
 OHMS/ M      OHMS/M                          MHOS/M        HZ
1.73870-002  1.04368-002  0.00000 + 000  2.14464-006  1.00 + 003
2.35061-002  6.62145-002  0.00000 + 000  1.54414-005  7.20 + 003
```

This calculation is performed in the Fortran program XY given in the Appendix (A.1, page 49).

3. MLDL PROPAGATION CALCULATIONS FROM GIVEN LINE PARAMETERS

In this chapter circuit models, equations, curves, computer printouts and programs are presented to illustrate the following specific propagation characteristics of the MLDL: (a) attenuation, phase, quarter wave length, (b) input impedance, (c) voltage amplitude, (d) current amplitude and phase.

3.1 Attenuation Phase and Quarter Wavelength

For the general equivalent circuit model in Fig. 3.1 the propagation function is defined as

$$\begin{aligned} \gamma(j\omega) &= \sqrt{Z(j\omega)\,Y(j\omega)} \\ &= \alpha(\omega) + j\beta(\omega) \qquad (3.1) \end{aligned}$$

where α, β are attenuation (dB/m) and phase (rad/m) respectively.

The characteristic impedance has the definition

$$Z_o(j\omega) = \sqrt{\frac{Z(j\omega)}{Y(j\omega)}} \qquad (3.2)$$

For the specific equivalent circuit model in Fig. 3.2 the series impedance $Z(j\omega)$ and shunt admittance $Y(j\omega)$ are calculated in the computer subroutine ZŌGAM. This subroutine appears in two versions in the Appendix (A.2, page 50). Version 1 computes $Z(j\omega) = R + j\omega L$ and $Y(j\omega) = j\omega C$ where $R = \Omega/1000$ ft., $L = 500\,\mu$ H/1000 ft., and $C = .2\,\mu$ F/100 ft. Version 2 of ZŌGAM calculates $Z(j\omega) = R(\omega) + j\omega L(\omega)$ and $Y(j\omega) = j\omega C$ from equations (2.1) through (2.4) of Chapter 2. For the sample calculations of Chapters 2 through 5 we have selected version 1.

A computer printout of attenuation, phase and quarter wave length for one frequency (100 Hz) appears below.

```
F (HZ)       ATTENUATION(DB/M)   PHASE (RAD/M)   QUARTER WAVE
                                                 WAVELENGTH (M)

1.00 + 002     4.894 - 004        5.999 - 005      2.618 + 004
```

The curves of attenuation, phase, and quarter wave length for $0 < f < 10$ KHz are shown in Figs. 3.3, 3.4, 3.5.

3.2 Input Impedance

The input impedance for the MLDL terminated in an arbitrary load impedance Z_L has the quivalent circuit shown in Fig. 3.6. For $Z_L = Z_o$, $Z_L = 0$ (short termination), $Z_L = \infty$ (open termination) the expressions for Z_{in} are

$$\Big[Z_{in}(j\omega)\Big]_{Z_L=Z_o} = Z_o(j\omega) \tag{3.3}$$

$$\Big[Z_{in}(j\omega)\Big]_{Z_L=0} \quad Z_o(j\omega)\,\frac{1 - e^{-2\ell\gamma(j\omega)}}{1 + e^{-2\ell\gamma(j\omega)}}\ , \tag{3.4}$$

and

$$\Big[Z_{in}(j\omega)\Big]_{Z_L=\infty} \quad Z_o(j\omega)\,\frac{1 + e^{-2\ell\gamma(j\omega)}}{1 - e^{-2\ell\gamma(j\omega)}} \tag{3.5}$$

respectively.

A computer printout of $Z_{in}(j\omega)$ for one frequency (100 Hz) for a line length $\ell = 500$ meters appears below.

INPUT IMPEDANCE VERSUS FREQUENCY FOR THREE TERMINATING IMPEDANCES

	Z_0 TERMINATION		SHORT TERMINATION	
F HZ	REAL(ZIN) OHMS	IMAG(ZIN) OHMS	REAL (ZIN) OHMS	IMAG (ZIN) OHMS
1.00 + 002	1.455 + 002	-1.367 + 002	8.20	5.106-001

OPEN TERMINATION

F HZ	REAL (ZIN) OHMS	IMAG (ZIN) OHMS
1.00 + 002	2.733 + 000	-4.852 + 003

The curves of each termination for Real (Zin) versus f and Imag (Zin) versus f are shown in Figs. 3.7, . . ., 3.12 for $0 < f < 10$ KHz. Note that when $Z_L = Z_o$, the input impedance is in fact equal to Z_o; consequently, Figs. 3.7 and 3.8 show the real and imaginary parts of Z_o, respectively.

3.3 Voltage Amplitude

Consider a one volt sine wave generator with 50 ohms impedance driving the MLDL with a short termination. The circuit model is shown in Fig. 3.13 where $E(j\omega)$ is the voltage response at the source end. The amplitude $|E(j\omega)|$ has the expression

$$\left| E(j\omega) \right| = \left| \frac{Z_o(j\omega)}{Z_o(j\omega) + 50} \right| \left| \frac{1 - e^{-2\ell\gamma(j\omega)}}{1 + e^{-2\ell\gamma(j\omega)}} \right| \tag{3.6}$$

The computer printout for a line length of 500 meters of $| E(j2\pi f) |$ for one frequency (100 Hz) appears below.

```
        SOURCE VOLTAGE AMPLITUDE RESPONSE
     USING SINE WAVE GENERATOR WITH 50 OHMS
         IMPEDANCE ...  CHARGING DOWN LINE

         F                    AMPLITUDE  RESPONSE
        HZ                          VOLTS
     1.00 + 002                  3.444 - 002
```

The curve of $|E(j2\pi f)|$ versus f for $0 < f < 10$ KHz appears in Fig. 3.14.

The computer program which performs the calculations of sections 3.1, 3.2, 3.3 is entitled RESPDATA and is given in the Appendix (A.3, page 51).

3.4 Current Amplitude and Phase

Consider the MLDL being charged down line when terminated in an arbitrary load impedance Z_L. The circuit model appears in Fig. 3.15.

The current response at any point x-meters from the generator for load impedances equal to 0, ∞, Z_o is given by

$$\left[I(j\omega, x) \right]_{Z_L = 0} = \frac{E_g}{Z_o(j\omega)} \; \frac{e^{-x\gamma(j\omega)} + e^{-(2\ell - x)\gamma(j\omega)}}{1 - e^{-2\ell\gamma(j\omega)}} \tag{3.7}$$

$$\left[I(j\omega, x) \right]_{Z_L = \infty} = \frac{E_g}{Z_o(j\omega)} \; \frac{e^{-x\gamma(j\omega)} - e^{-(2\ell - x)\gamma(j\omega)}}{1 + e^{-2\ell\gamma(j\omega)}} \tag{3.8}$$

and

$$\left[I(j\omega, x) \right]_{Z_L = Z_o} = \frac{E_g \, e^{-x\gamma(j\omega)}}{Z_o(j\omega)} \; . \tag{3.9}$$

The computer printout for current amplitude and phase appears below for a total line length of 1500 meters for a 1 volt sinusoidal generator.

```
        CURRENT RESPONSE AS FUNCTION OF POSITION ON LINE
                  FOR THREE DIFFERENT TERMINATIONS

                 OPERATING FREQUENCY IS 7.2 + 003 HZ

            ALL AMPLITUDE AND PHASE UNITS IN AMPERES
                      AND RADIALS, RESPECTIVELY

DISTANCE FROM     OPEN TERMINATION        SHORT TERMINATION
     TOP

    METERS      AMPLITUDE    PHASE       AMPLITUDE     PHASE
      3         2.445-002   -9.821-001   1.594-002    1.196 + 000
      6         2.452-002   -9.841-001   1.586-002    1.194 + 000
      -             -            -           -             -
      -             -            -           -             -
      -             -            -           -             -

    1500        0.000 + 000  0.000 + 000 2.402 - 002  -1.649 + 000

                       ZO  TERMINATION
DISTANCE FROM TOP
     METERS              AMPLITUDE                     PHASE
       3                 1.976 - 002                1.088 - 001
       -                    ---                         ---
       -                    ---                         ---
       -                    ---                         ---
      1500               1.548 - 002               -2.130 - 001
```

The curves of amplitude and phase versus distance from the top appear in Figs. 3.16, ..., 3.19; these curves were computed using the computer program entitled CURRESP which is given in the Appendix (A.4, page 53).

CHAPTER 4

COUPLER LOADED MLDL CALCULATIONS

In this chapter an equivalent circuit for the n coupler loaded MLDL and voltage-current expressions for any coupler position are developed. Computer printouts, programs and curves of current responses are illustrated.

To carry out propagation calculations of the coupler loaded MLDL consider the circuit of Fig. 4.1 where each coupler has the equivalent circuit

$$Z_C(j\omega) = R_C + j\omega L_C \tag{4.1}$$

E_g is a 1 volt sinusoidal generator, and $Z_g = 50$ ohms.

Using the ABCD 4 terminal network parameters enables a matrix equation of the form †

$$\begin{bmatrix} E_g \\ I_g \end{bmatrix} = \begin{bmatrix} 1 & Z_g \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} 1 & Z_c \\ 0 & 1 \end{bmatrix} \cdots \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix} \begin{bmatrix} 1 & Z_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ I_L \end{bmatrix}$$

$$\equiv \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} O \\ I_L \end{bmatrix} \tag{4.2}$$

Now the kth section of line has the definition

---

† The dependence of network parameters on $j\omega$ is omitted for space economy.

$$\begin{bmatrix} A_k & B_k \\ C_k & D_k \end{bmatrix} = \frac{1}{Z_o} \begin{bmatrix} Z_o \cosh \zeta_k \gamma & Z_s^2 \sinh \zeta_k \gamma \\ \sinh \zeta_k \gamma\, a & Z_o \cosh \zeta_k \gamma \end{bmatrix} \qquad (4.3)$$

where $\zeta_k = x_k - x_{k-1}$.

We are interested in computing the voltage and current at each coupler position x_k. From (4.2) notice $E_g = 1 = BI_L$ and $I_g = DI_L$.

Therefore $I_g = D/B$.

At $x = x_1$ the voltage and current are given by

$$\begin{bmatrix} E(x_1) \\ I(x_1) \end{bmatrix} = \begin{bmatrix} 1 & -Z_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}^{-1} \begin{bmatrix} 1 & -Z_g \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ I_g \end{bmatrix} \qquad (4.4)$$

At $x = x_k$, the voltage and current expressions are

$$\begin{bmatrix} E(x_k) \\ I(x_k) \end{bmatrix} = \begin{bmatrix} 1 & -Z_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_k & B_k \\ C_k & D_k \end{bmatrix}^{-1} \cdots \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}^{-1} \begin{bmatrix} 1 & -Z_g \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ I_g \end{bmatrix} \qquad (4.5)$$

The computer program ALLCPLR performs the current response calculations and is given in the Appendix (A.5, page 55) along with the subroutine for calculating the overall ABCD matrix of the coupler loaded transmission line (A.6, page 57). The computer print-out from a sample calculation of (4.5) appears below for current response.†

---

† Additional coupler configurations, line lengths, and operating frequencies were input to this program by request of the Sponsor. The results were delivered to Mr. E. Kerut in June, 1972.

SINGLE STRAND LINE WITH 12 COUPLERS
DOWN MODE WITH GENERATOR AT SURFACE
GENERATOR CHARACTERISTICS... EG = 1 VOLT ZG = 50 OHMS
F = 2 KHZ
THE FOLLOWING LINE PARAMETERS ARE USED ---
R = 5 OHMS/10^3 FT L = 500 MICROHENRYS/10^3 FT
C = .2 MICROFARADS/10^3 FT

THE FOLLOWING CURRENT RESPONSE IS COMPUTED
AT EACH COUPLER POSITION

DISTANCE FROM TOP (METERS)	AMPLITUDE (AMPS)	PHASE (RADIANS)
0	1.94719-002	-2.88721-001
10	1.9495-002	-2.92767-001
≡	≡	≡
500	2.00345-002	-3.63656-001

Current versus line position curves are also presented in Figs. 4.2 and 4.3.

CHAPTER 5

SINGLE COUPLER MLDL UPMODE TRANSMISSION

In this chapter equivalent circuits, equations, computer printouts, programs, and curves are presented for upmode transmission on the MLDL from a single coupler at a given position.

Consider the circuit shown in Fig. 5.1. The voltage generator has been moved from above water to the coupler position x meters down line and a short has been inserted for the terminal load impedance. Since the coupler impedance is in series with the input impedance to the short circuit section of the MLDL an equivalent impedance is used.

$$Z_{eq}(\ell - x,\ j\omega) = Z_c(j\omega) + Z_{in}(\ell - x,\ j\omega)$$

An equivalent circuit to the circuit of Fig. 5.1 is shown in Fig. 5.2.

Now the input impedance to the short circuit section of MLDL is given by

$$Z_{in}(\ell - x,\ j\omega) = \frac{1 - \exp\{-2(\ell - x)\gamma(j\omega)\}}{1 + \exp\{-2(\ell - x)\gamma(j\omega)\}} \qquad (5.1)$$

The voltage response at the above water level is given by

$$E(x,\ j\omega) = E_c \frac{Z_o(j\omega)\, e^{-x\gamma(j\omega)}}{Z_o(j\omega) + Z_{eq}(\ell - x,\ j\omega)} \ \frac{1 + \rho_g(j\omega)}{1 - \rho_{eq}(j\omega)\rho_g \epsilon^{-2\ell\gamma(j\omega)}}$$

$$(5.2)$$

where ρ_{eq} and ρ_g are voltage reflection coefficients, i.e.,

$$\rho_{eq} = \frac{Z_{eq} - Z_o}{Z_{eq} + Z_o} \quad \text{and} \quad \rho_g = \frac{Z_g - Z_o}{Z_g + Z_o} \, . \tag{5.3}$$

The current expression at the above water level is

$$I(x, j\omega) = E_c \, \frac{e^{-x\gamma(j\omega)}}{Z_o(j\omega) + Z_{eq}(\ell - x, j\omega)} \; \frac{1 - \rho_g(j\omega)}{1 - \rho_{eq}(j\omega)\rho_g(j\omega)\, e^{-2x\gamma(j\omega)}} \tag{5.4}$$

The computer printouts for voltage and current are displayed below and have been calculated using the computer program UPMODE given in the Appendix (A. 7, page 56).†

```
            SINGLE STRAND LINE WITH ONE COUPLER
              UPMODE USING 1 VOLT 6 KHZ SOURCE
      R  = 5 OHMS/1000 FT     L  =  500 MICROHENRYS/1000 FT
                 C  =  .2 MICROFARADS/1000 FT
      THE FOLLOWING CURRENT RESPONSE IS AT SURFACE
       AS FUNCTION OF DISTANCE FROM COUPLER SOURCE


     DISTANCE FROM TOP          AMPLITUDE          PHASE
         (METERS)                 (AMPS)         (RADIANS)
            50                 1.17647-002      3.83396-001
            ≡
           2000                1.39387-002     -2.47144+000
```

---

† On request of the sponsor different coupler levels, operation frequencies, and line lengths were input to this program. The results were delivered to Mr. E. Kerut in June, 1972.

THE FOLLOWING VOLTAGE RESPONSE IS AT SURFACE AS FUNCTION OF DISTANCE FROM COUPLER SOURCE

DISTANCE FROM TOP (METERS)	AMPLITUDE (VOLTS)	PHASE (RADIANS)
50	5.88233-001	3.83396-001
≡	≡	
2000	5.96933-001	-2.47144 + 000

The amplitude curves for voltage and current versus distance are shown in Figs. 5.3, ..., 5.6.

REFERENCES

1. Ryder, J. D., "Networks, Lines and Fields", Prentice-Hall, 1949.
2. U. S. Coast Guard National Data Buoy Development Project, Report No. 601107, "Data Line Analysis and Telemetry Specification", Arthur D. Little, Inc.
3. Weeks, J. L., "Electromagnetic Theory for Engineering Applications", John Wiley and Sons, Inc., 1964, pp. 482-493.

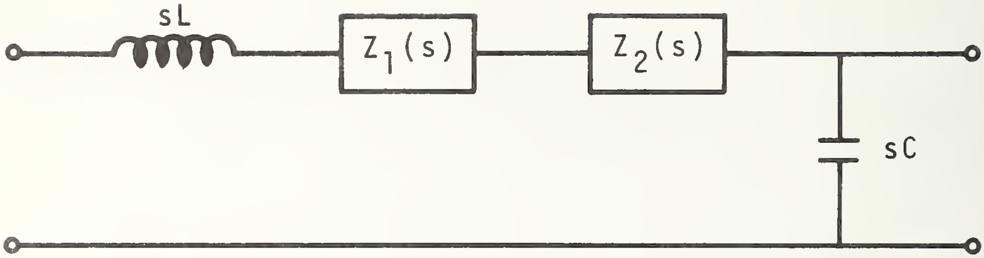

Figure 2.1 Equivalent circuit per unit length.

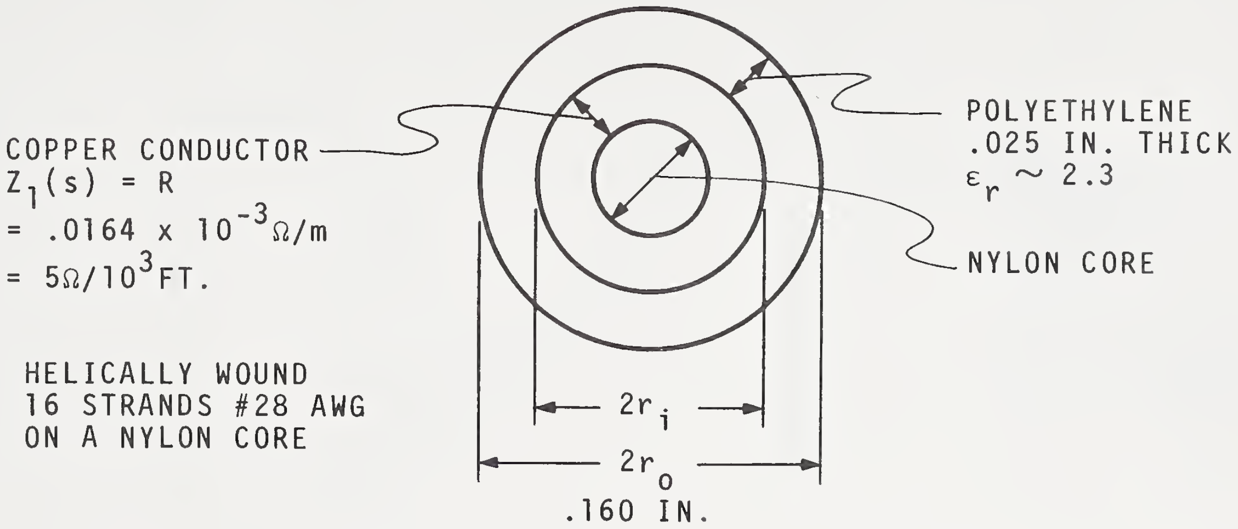

Figure 2.2 Cross section of single strand line.

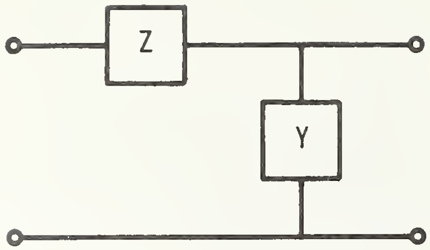

Figure 3.1 General equivalent circuit per unit length of MLDL.

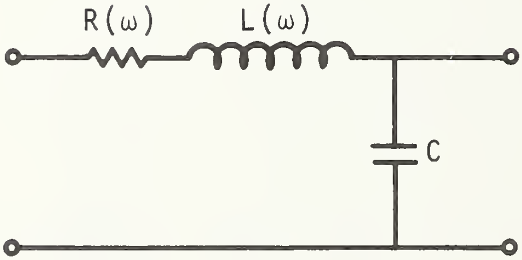

Figure 3.2 Equivalent circuit per unit length of MLDL in terms of the parameters R, L, and C.

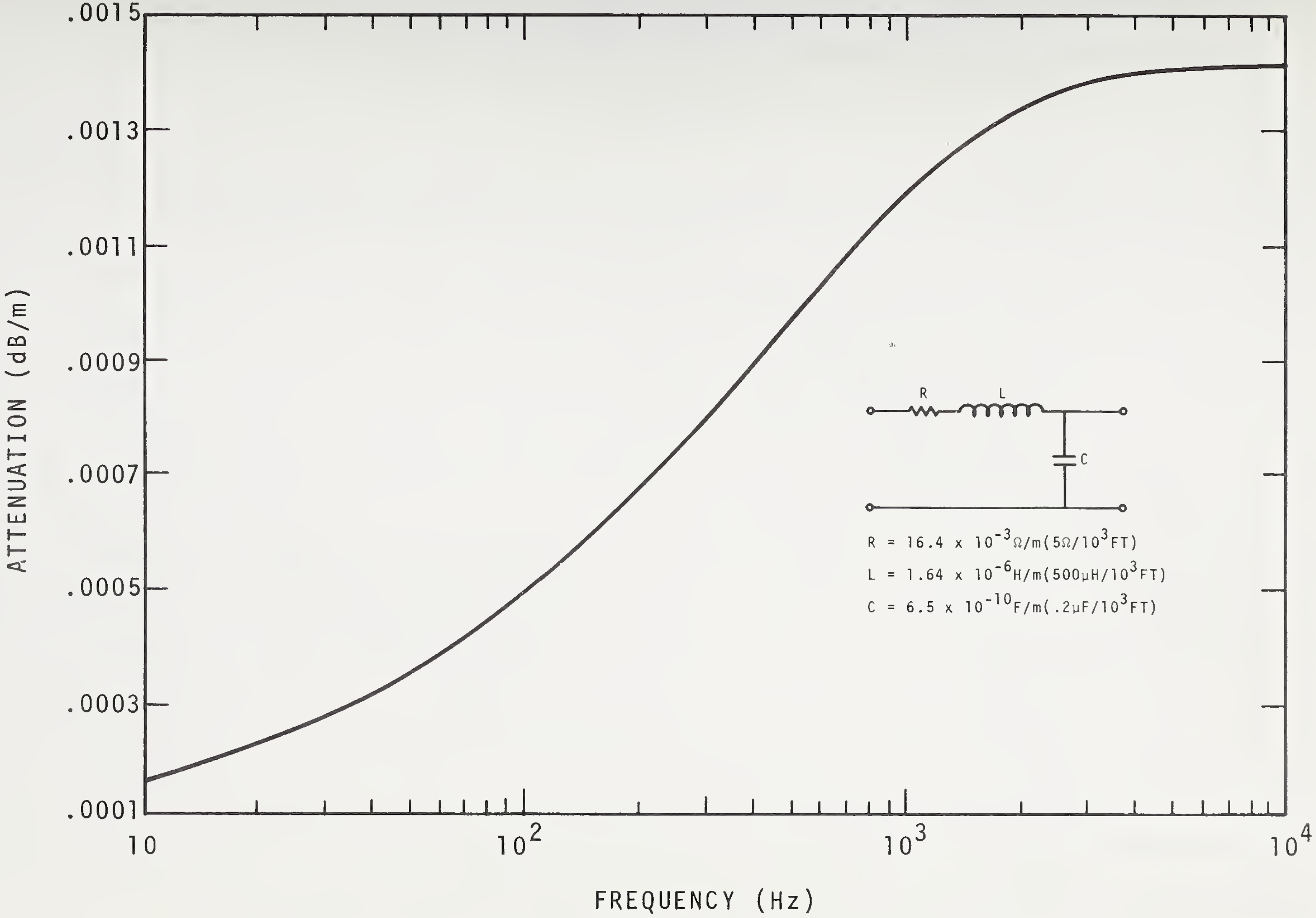

Figure 3. 3 Attenuation versus frequency.

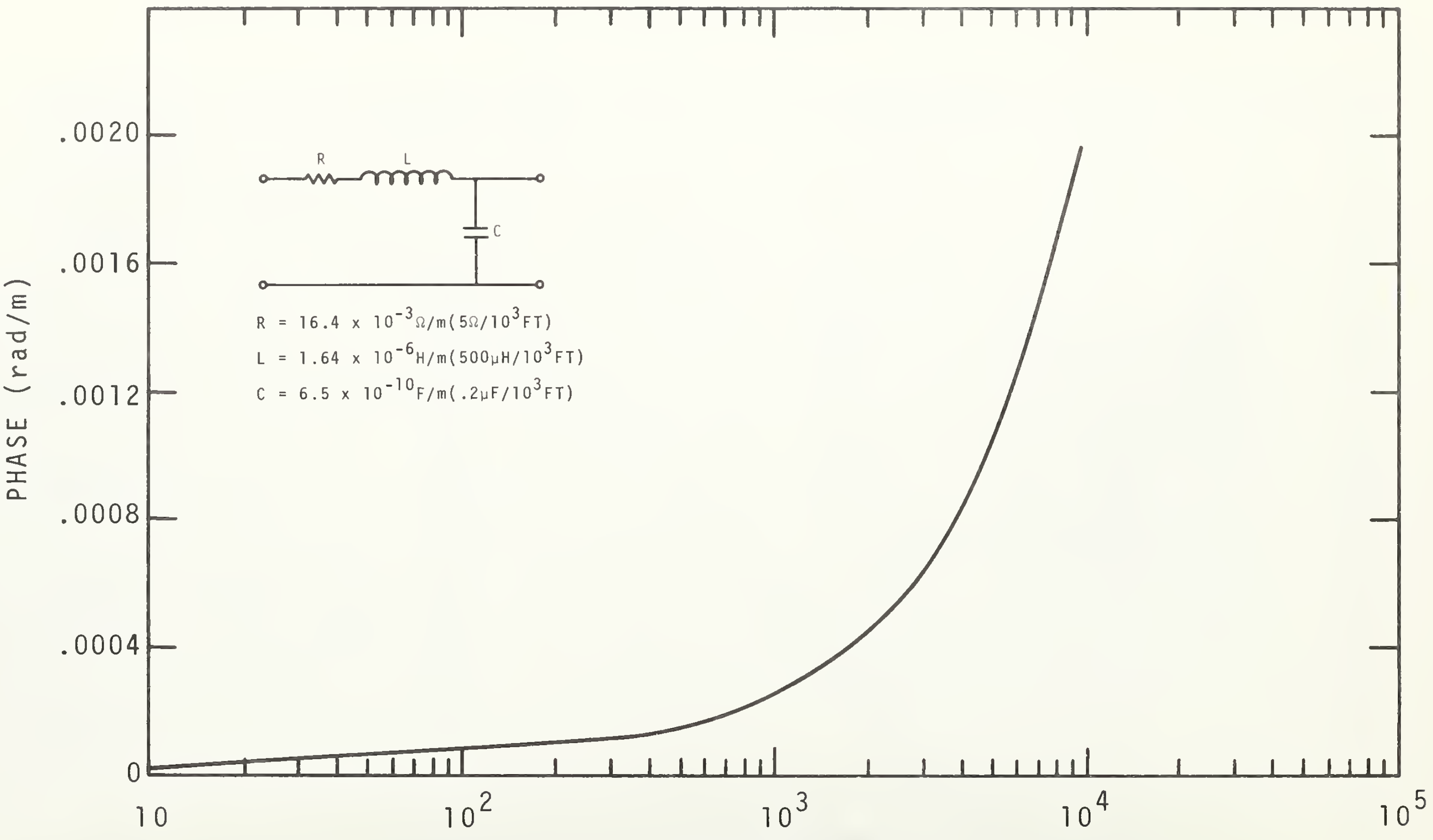

Figure 3.4 Phase versus frequency.

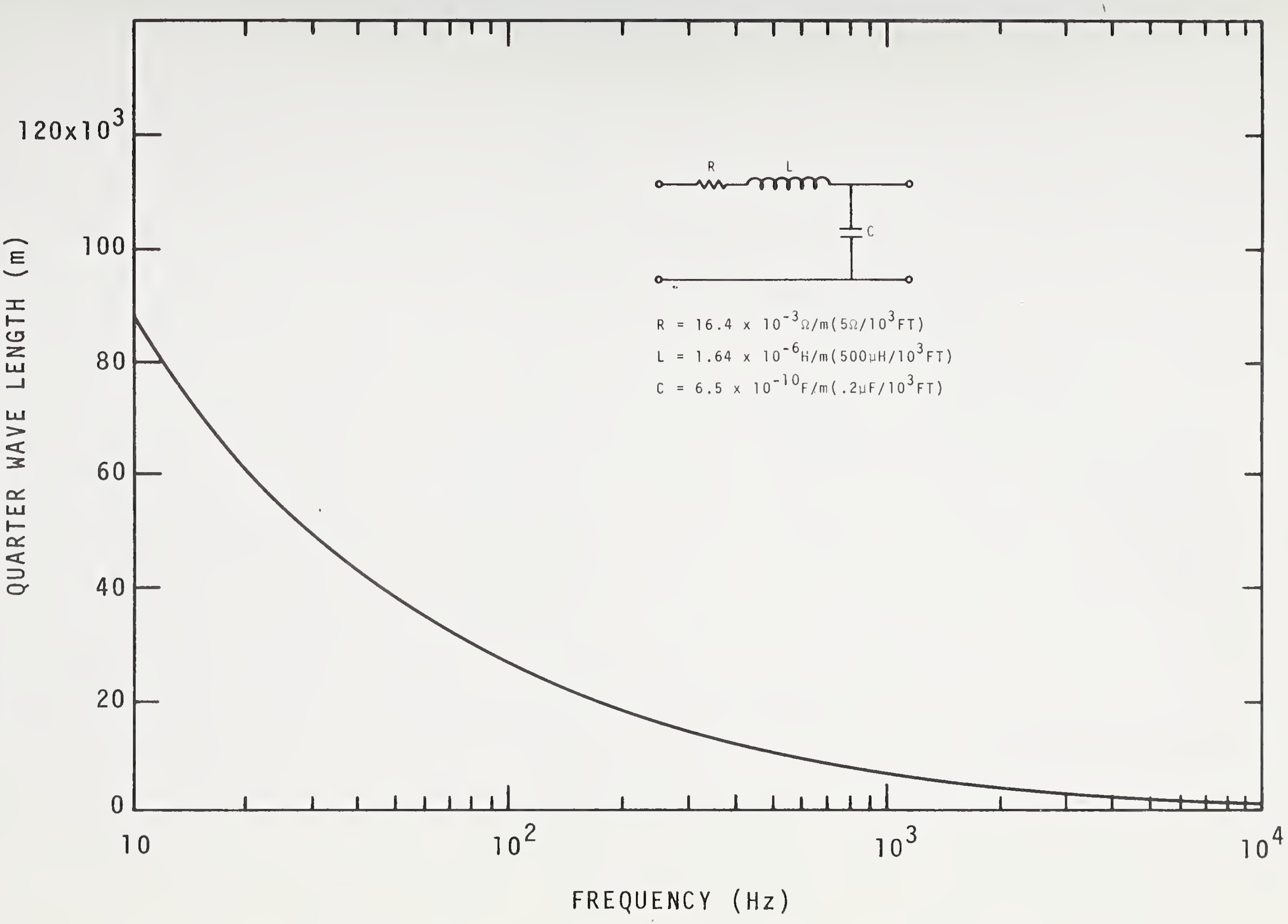

Figure 3.5 Quarter wave length versus frequency.

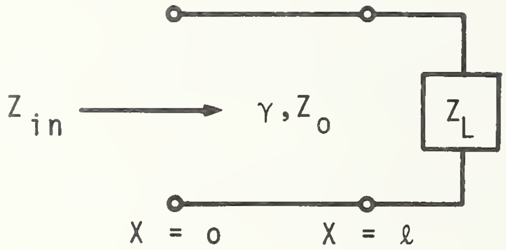

Figure 3. 6 Equivalent circuit for input impedance of MLDL terminated in arbitrary load impedance.

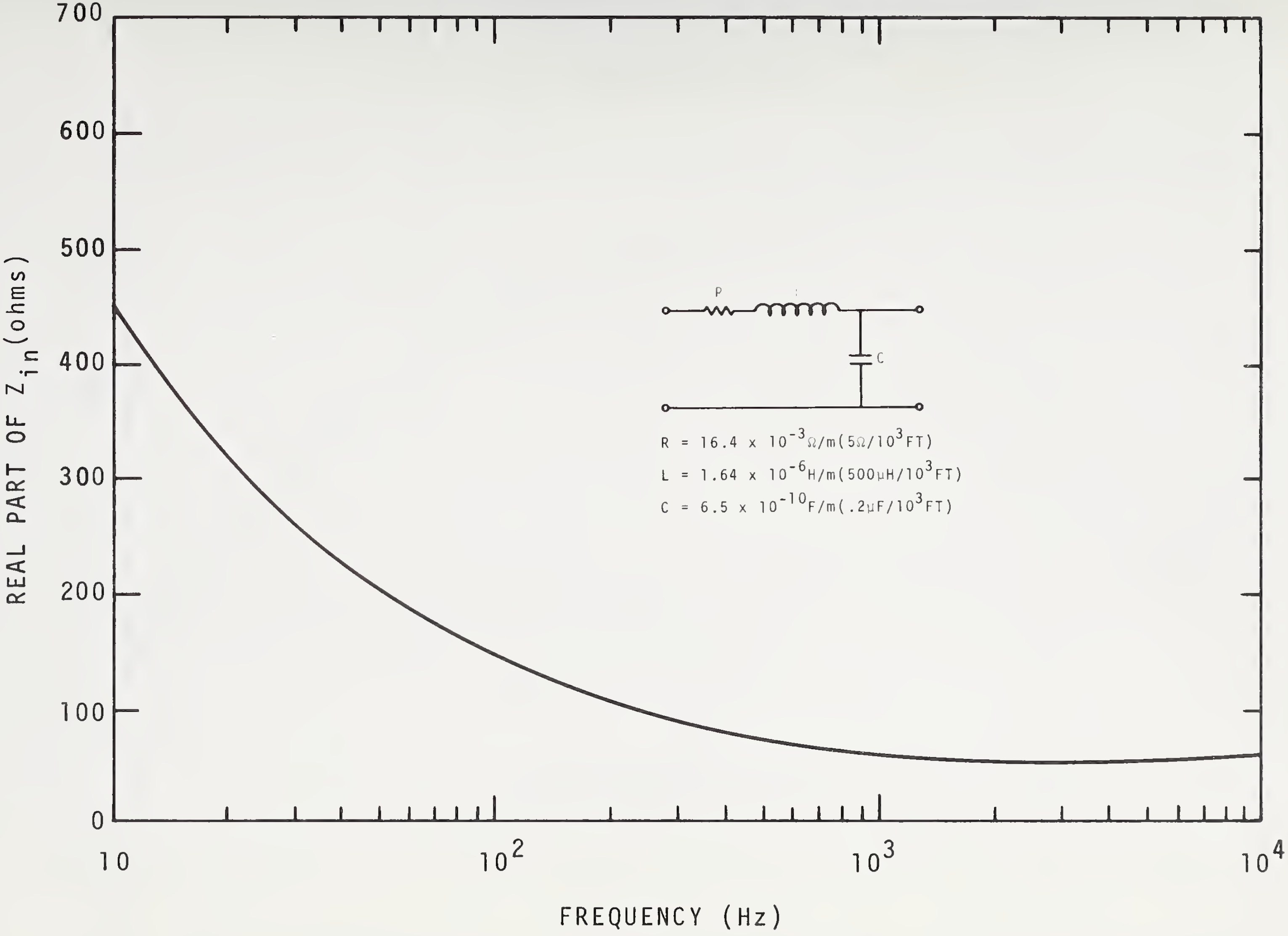

Figure 3.7 Real part of input impedance versus frequency Z_o termination.

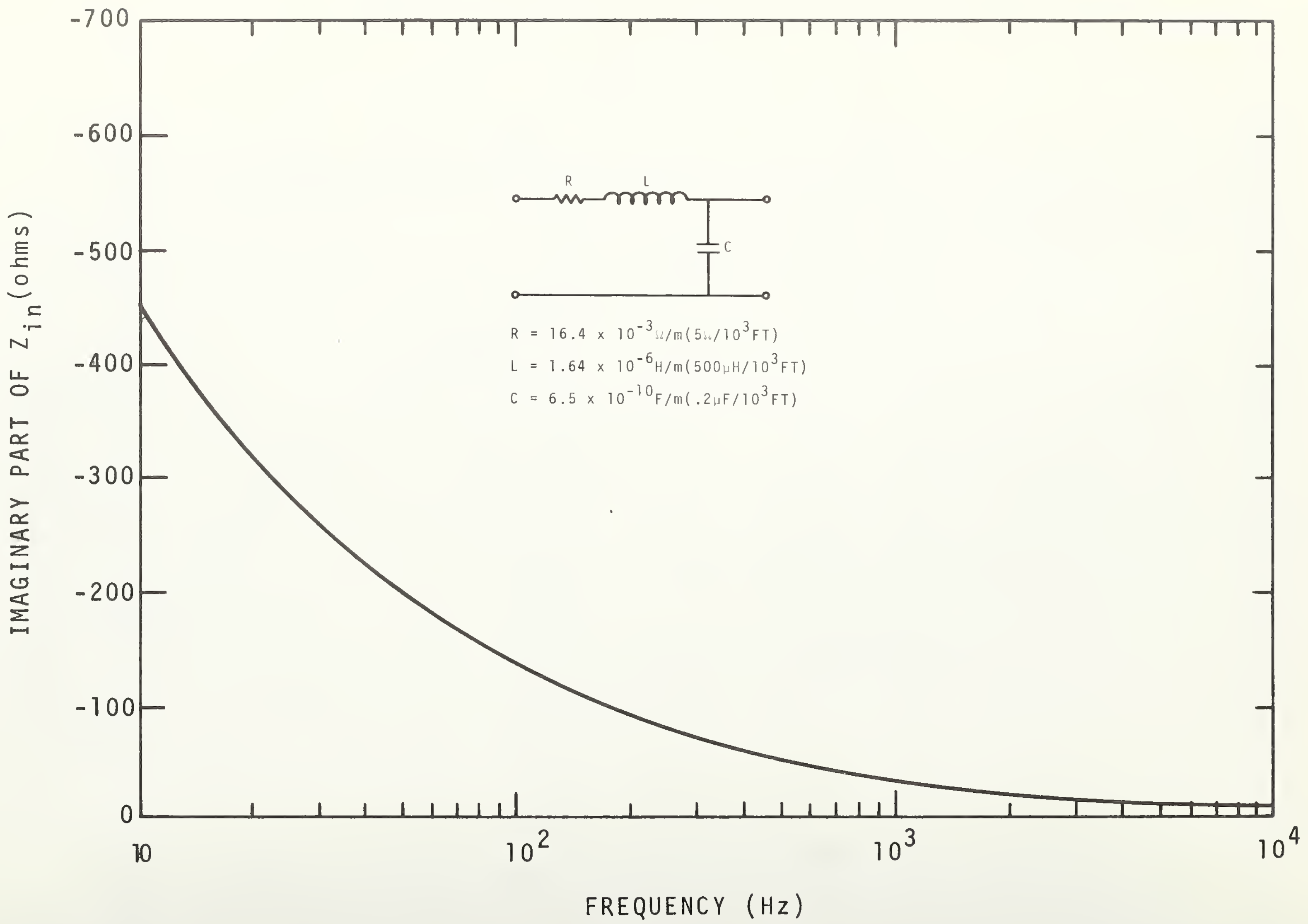

Figure 3.8 Imaginary part of input impedance versus frequency Z_o termination.

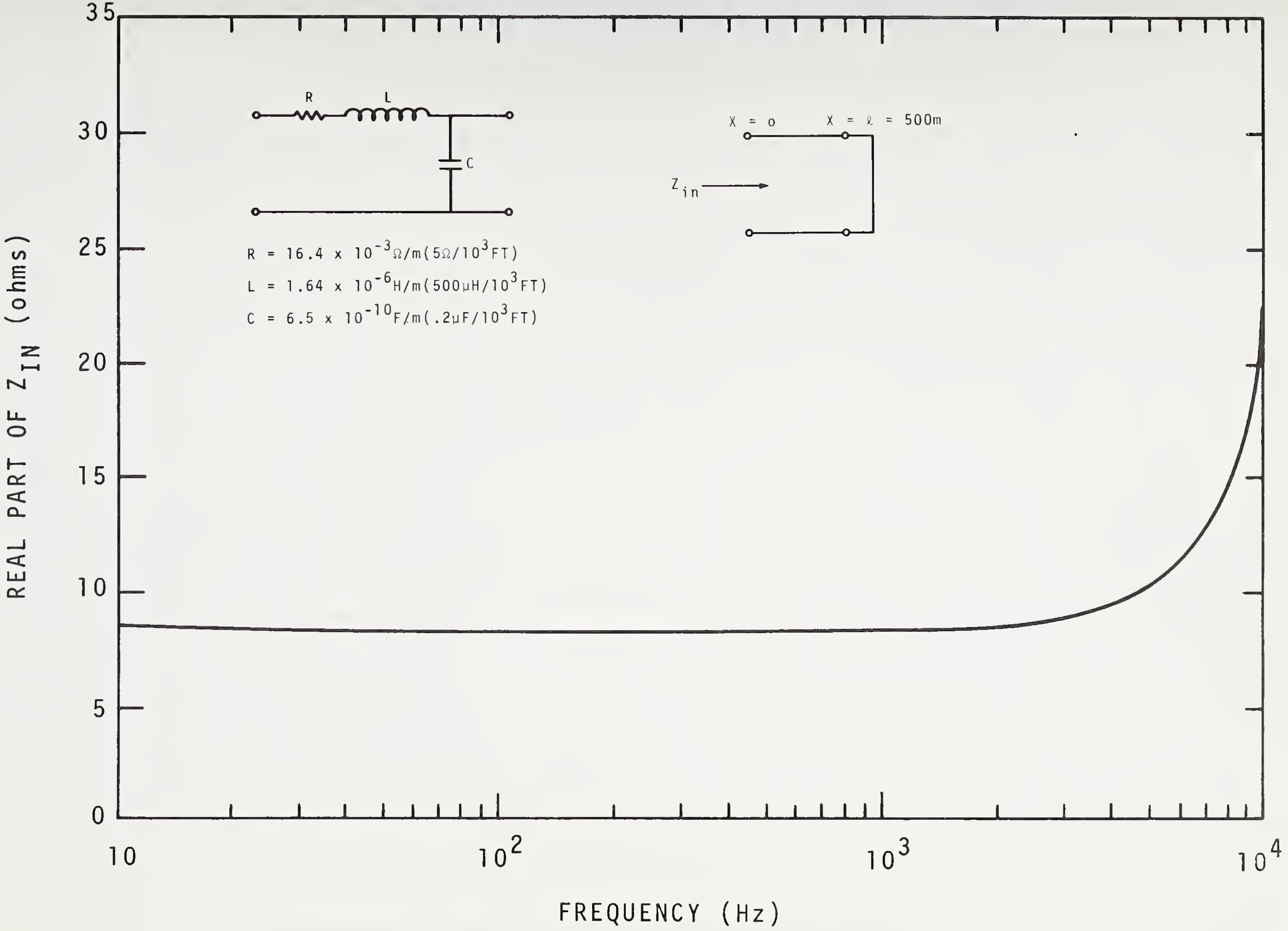

Figure 3.9 Real part of input impedance versus frequency short-circuit termination.

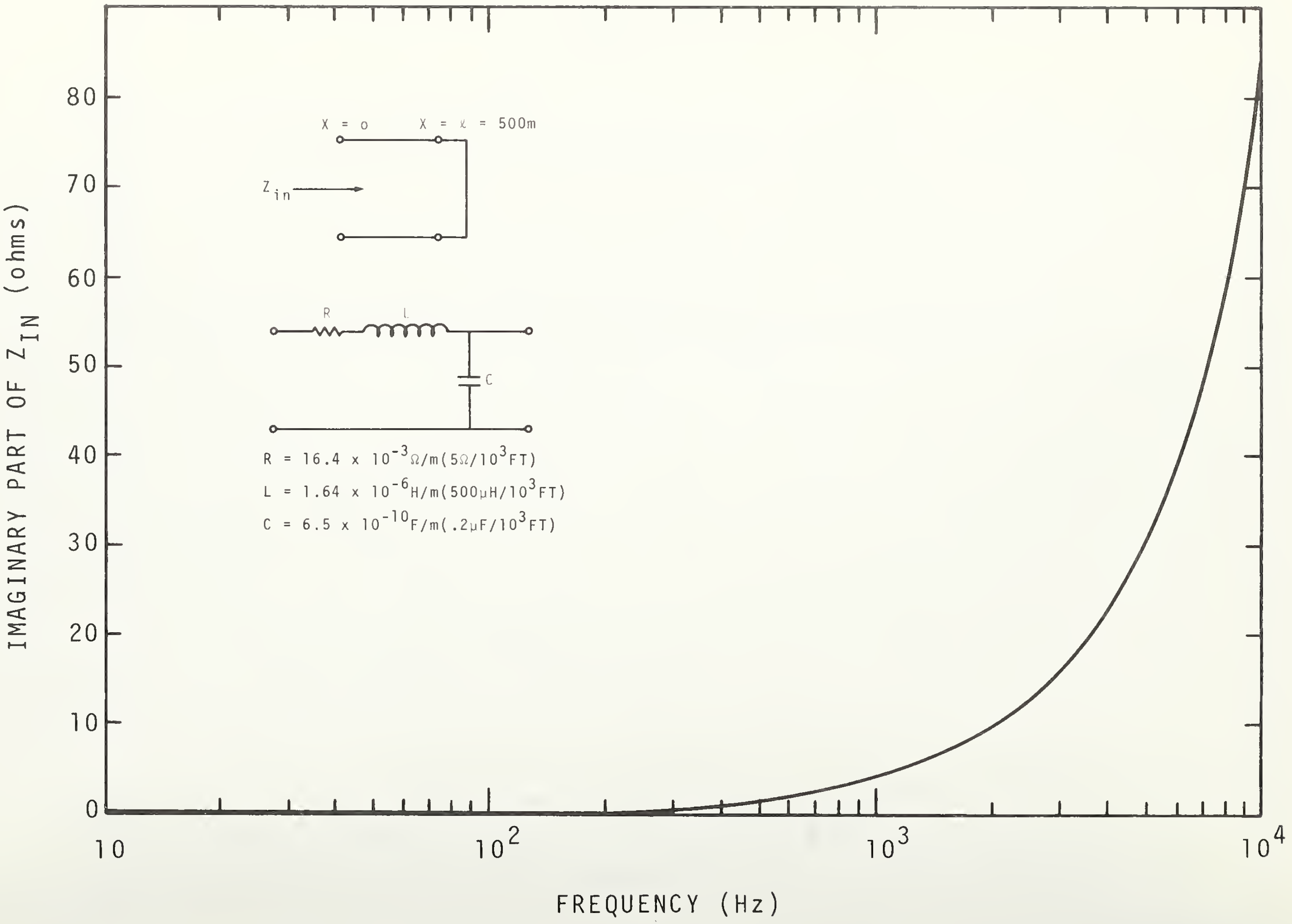

Figure 3.10 Imaginary part of input impedance versus frequency short-circuit termination.

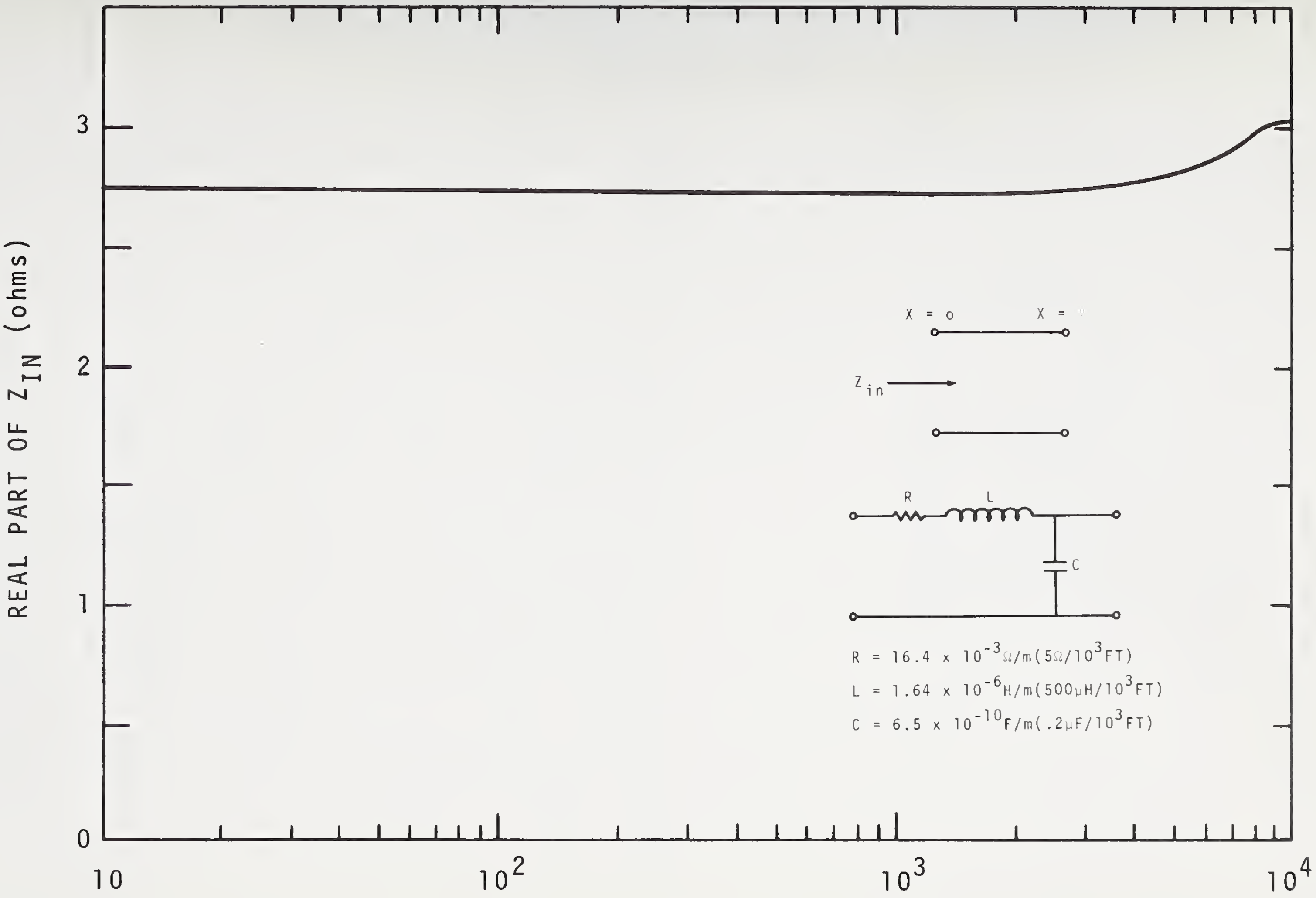

Figure 3.11 Real part of input impedance versus frequency open-circuit termination.

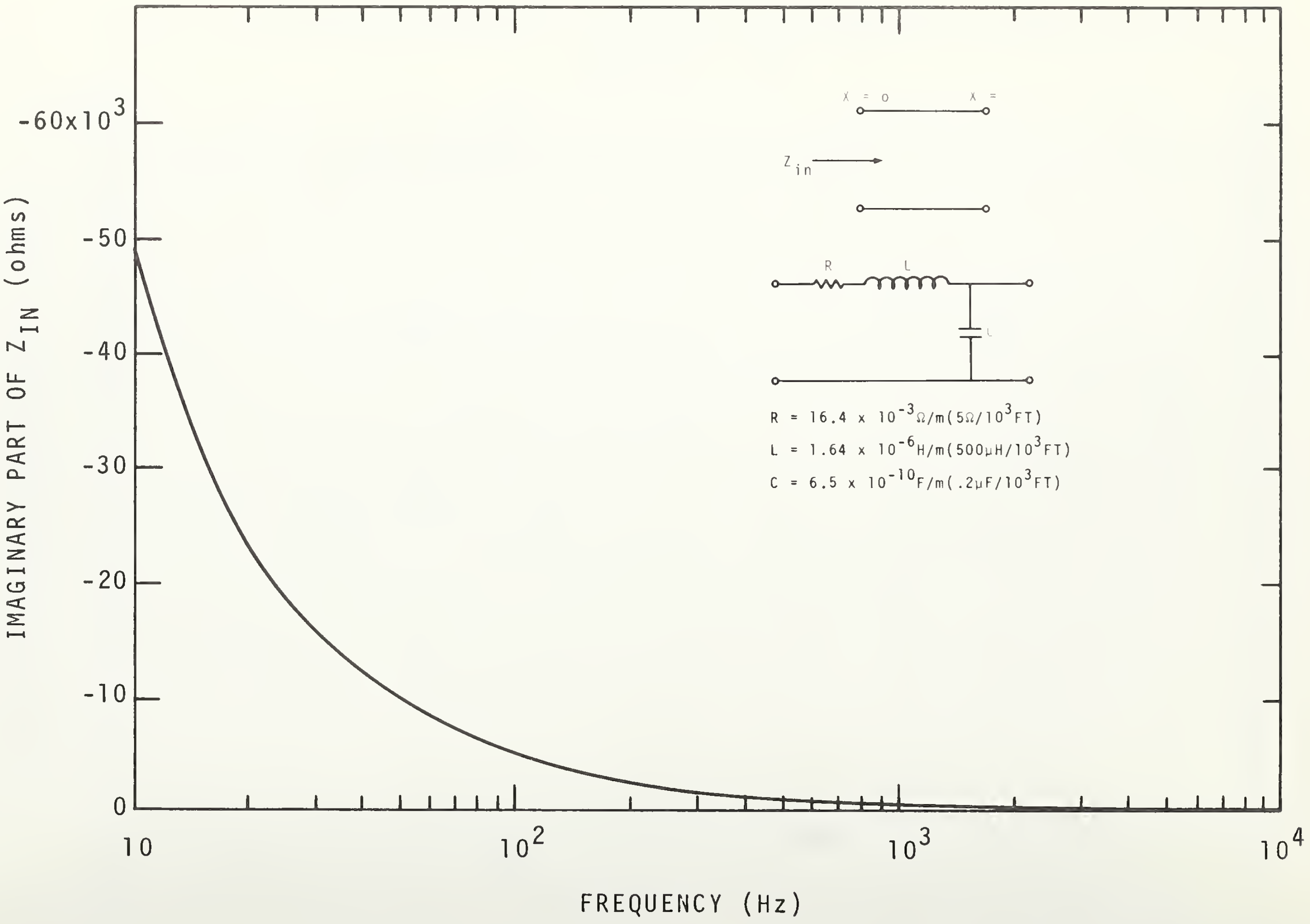

Figure 3.12 Imaginary part of input impedance versus frequency open-circuit termination.

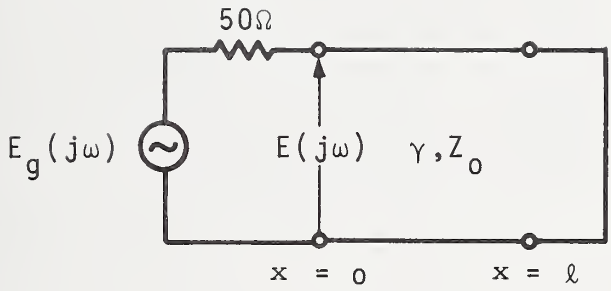

Figure 3.13 Equivalent circuit for source voltage response of MLDL with short termination.

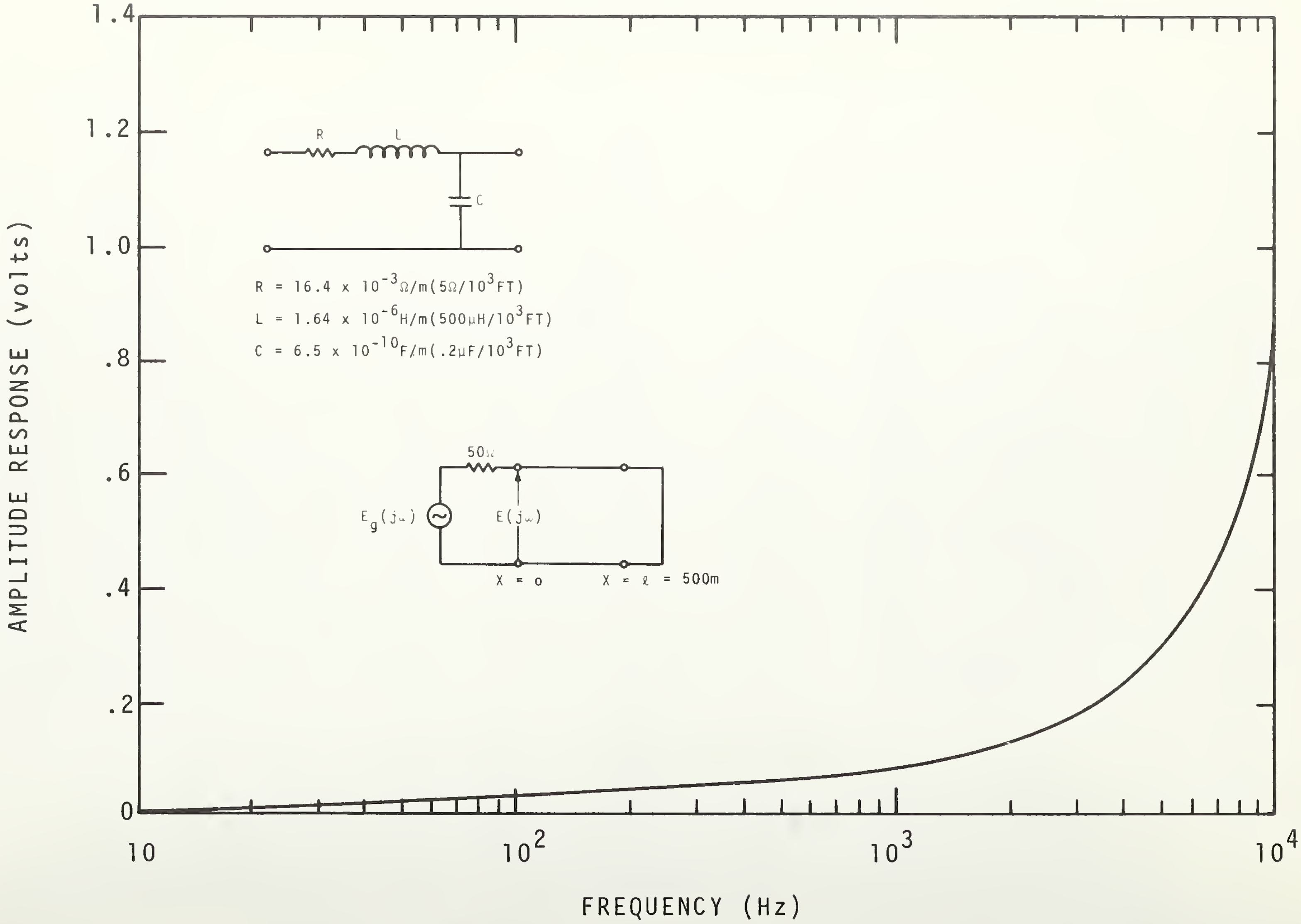

Figure 3.14 Input voltage amplitude response versus frequency short-circuit termination.

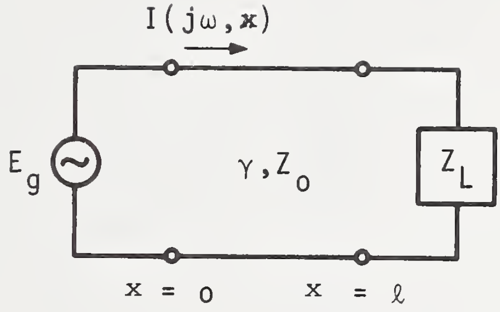

Figure 3.15 Equivalent circuit for current response for variable positions on the MLDL.

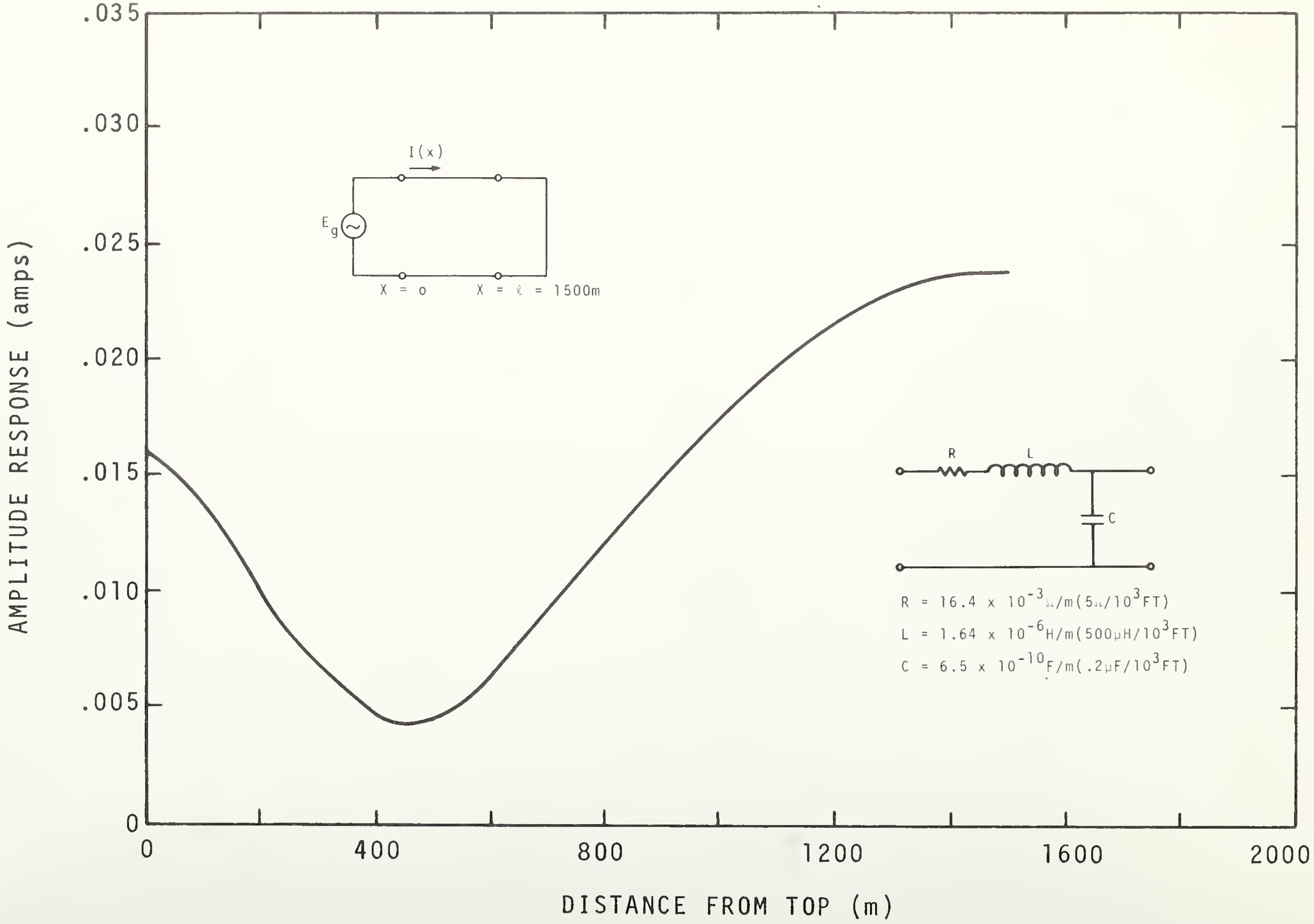

Figure 3.16 Current amplitude as function of position on line 7.2 KHz sine wave generator short-circuit termination.

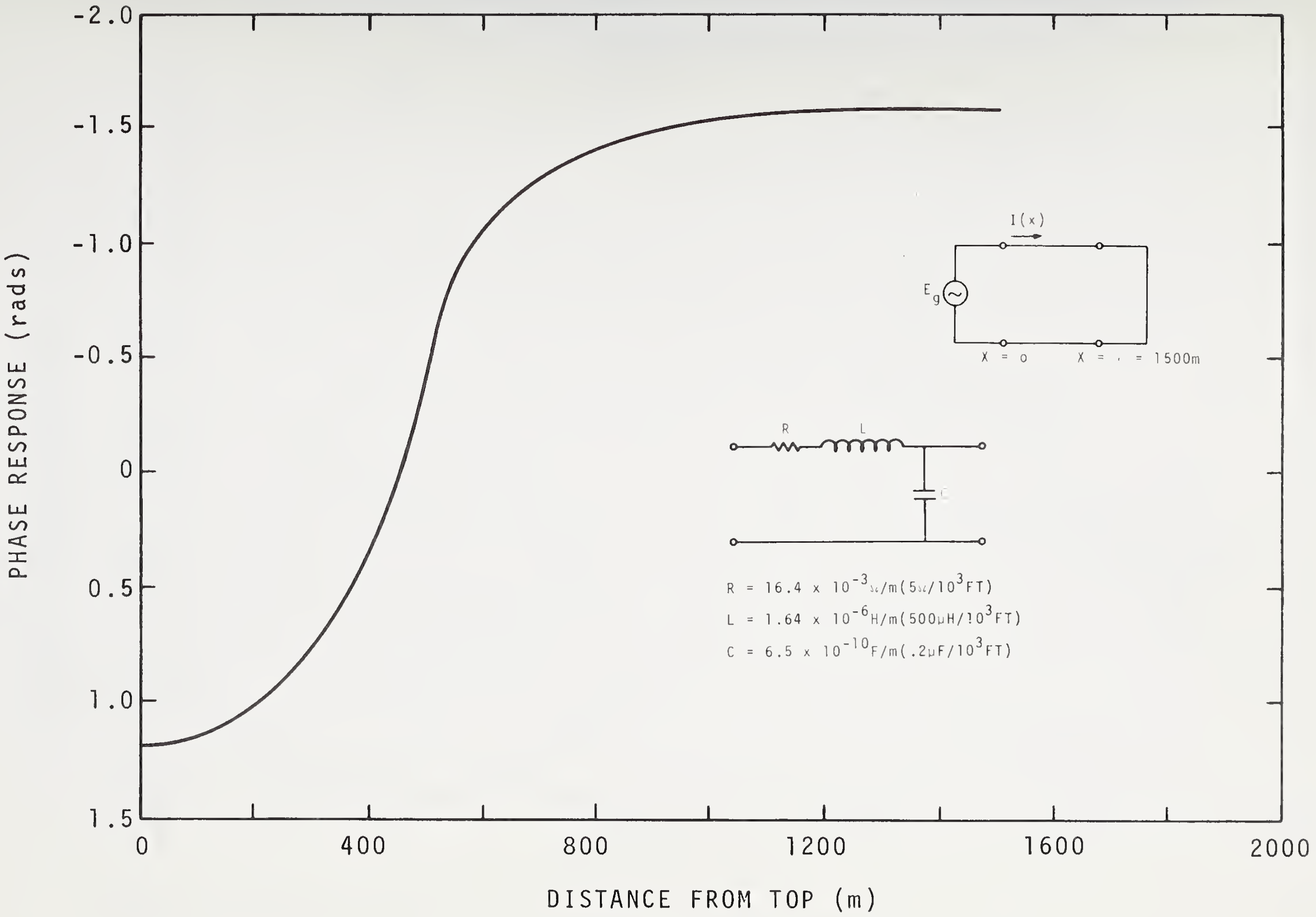

Figure 3.17 Current phase as function of position on line 7.2 KHz sine wave generator short-circuit termination.

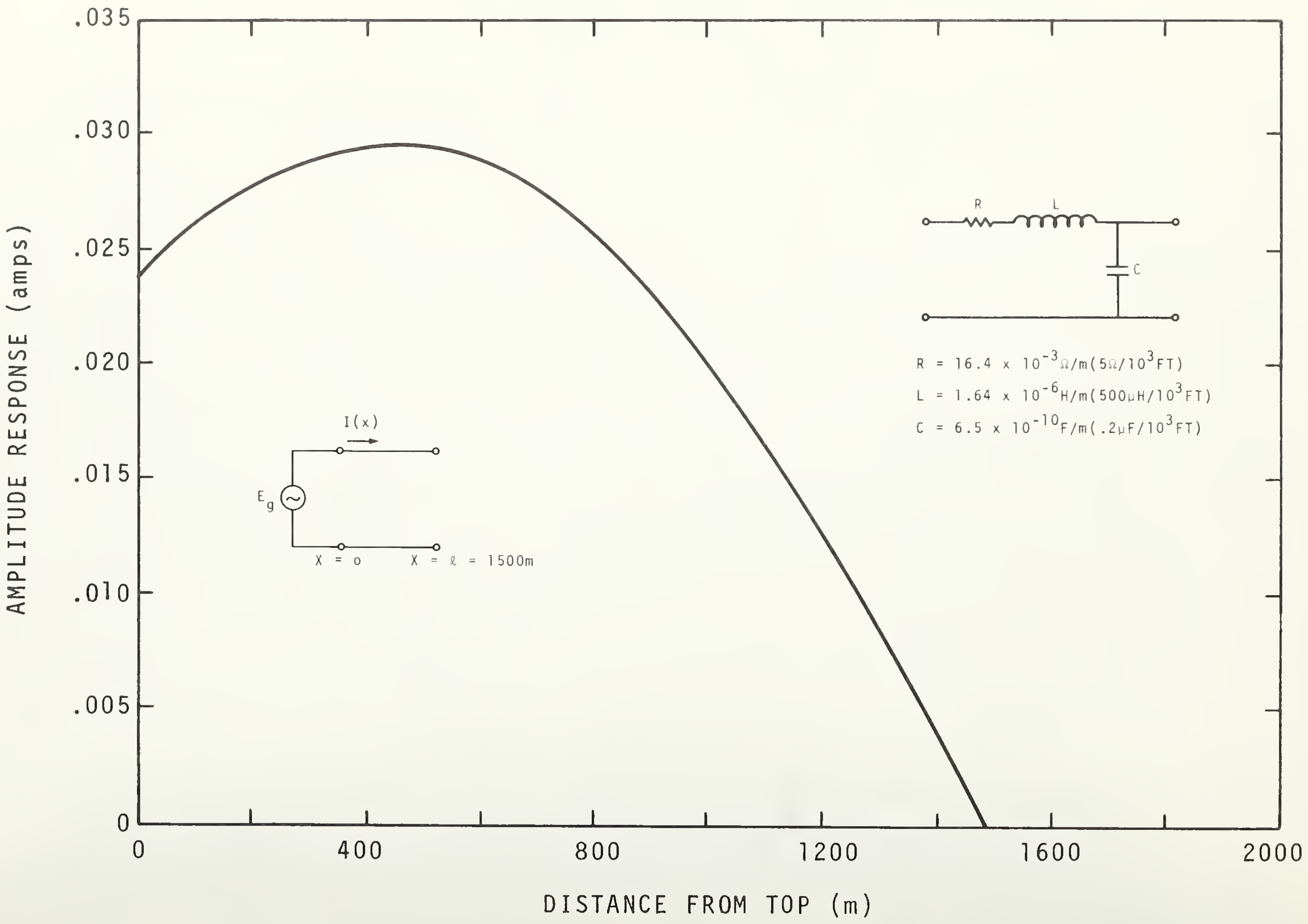

Figure 3.18 Current amplitude as function of position on line 7.2 KHz sine wave generator open-circuit termination.

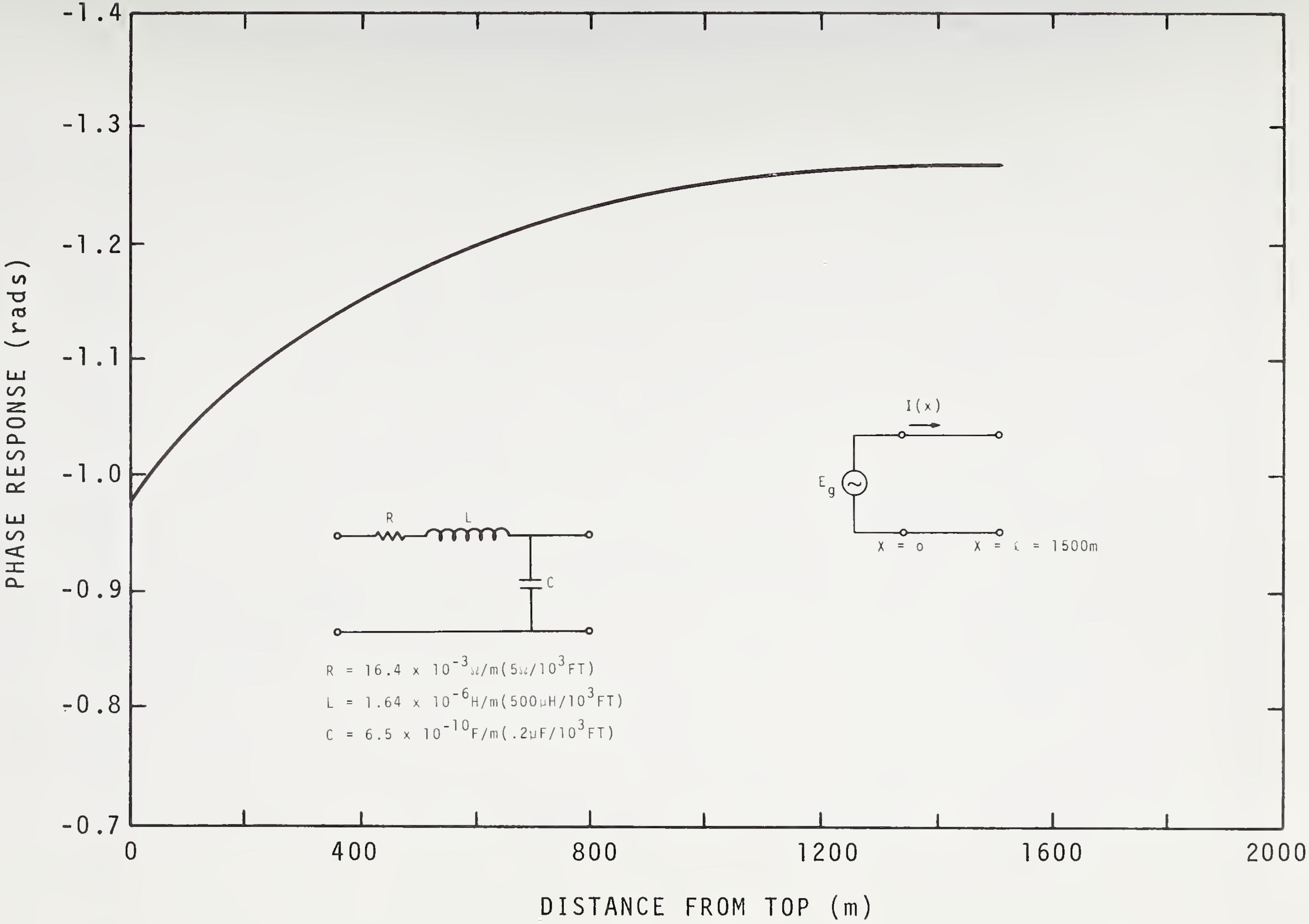

Figure 3.19 Current phase as function of position on line 7.2 KHz sine wave generator open-circuit termination.

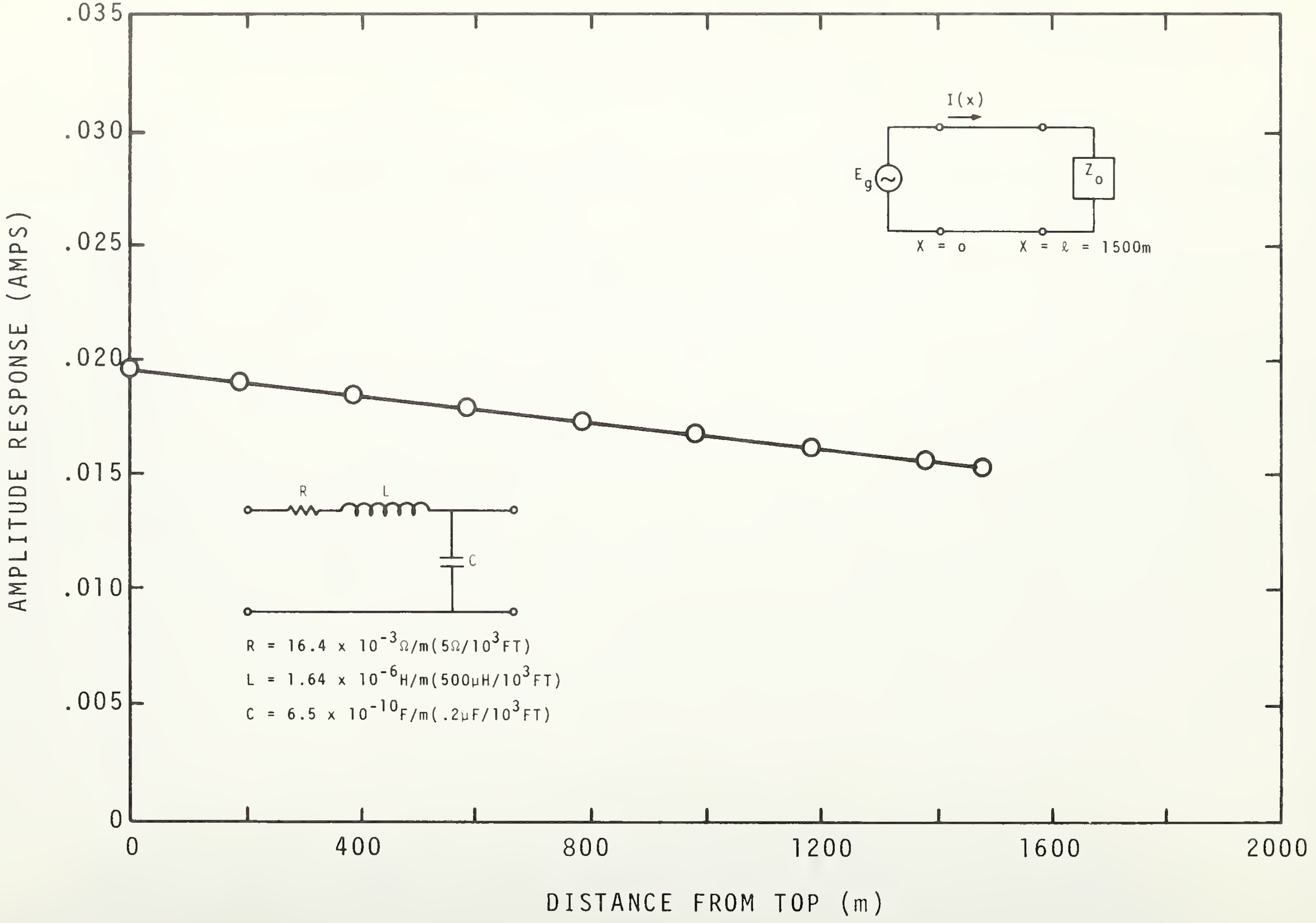

Figure 3.20 Current amplitude as function of position on line 7.2 KHz sine wave generator characteristic impedance (Z_o) termination.

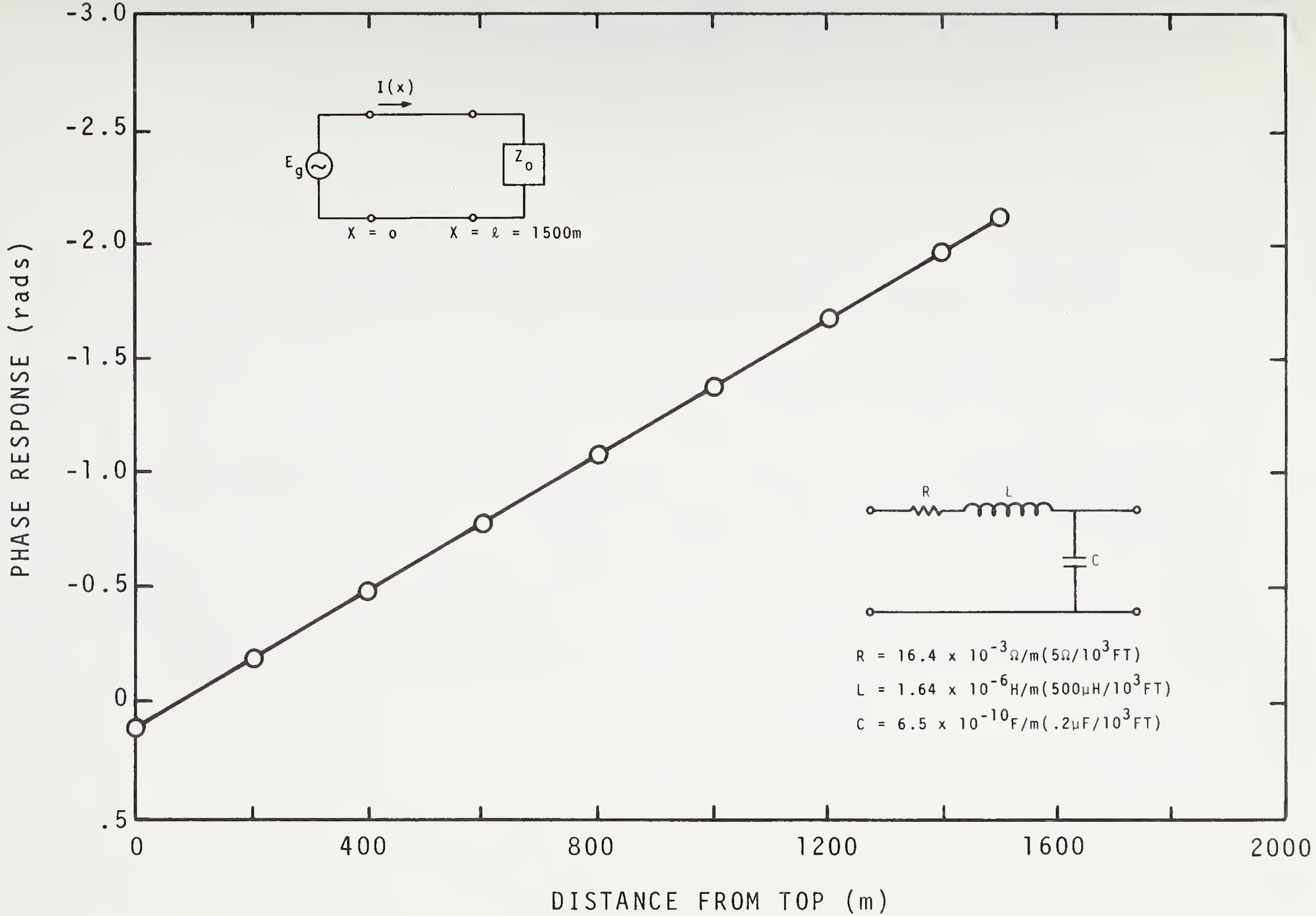

Figure 3.21 Current phase as function of position on line 7.2 KHz sine wave generator characteristic impedance (Z_o) termination.

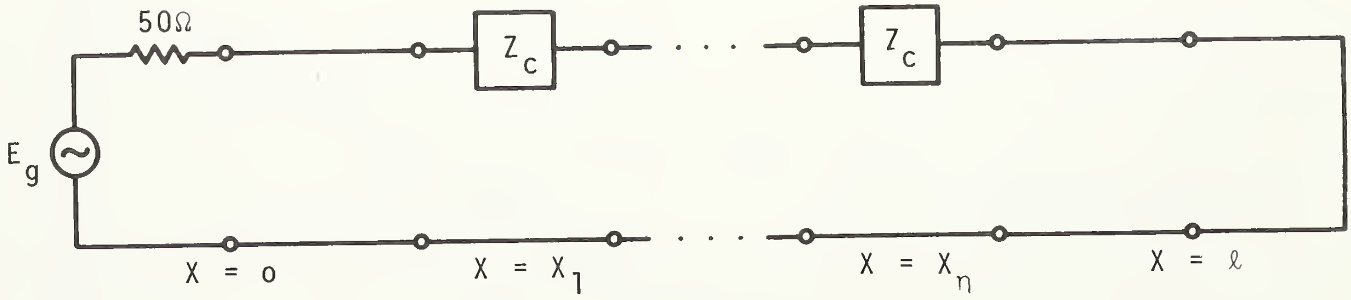

Figure 4.1 Equivalent circuit for coupler loaded MLDL.

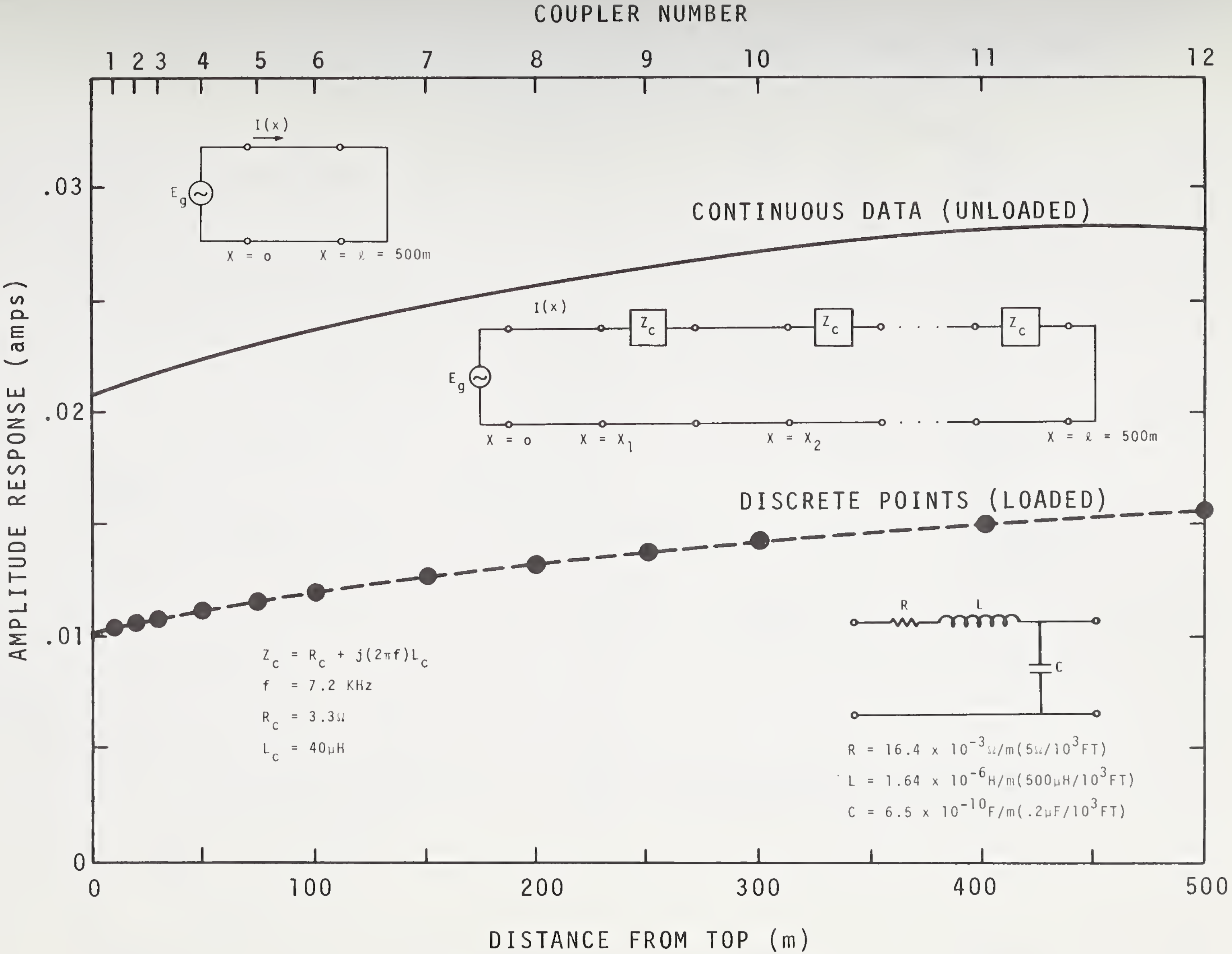

Figure 4.2 Current amplitude as function of position on loaded and unloaded line for 7.2 KHz sine wave.

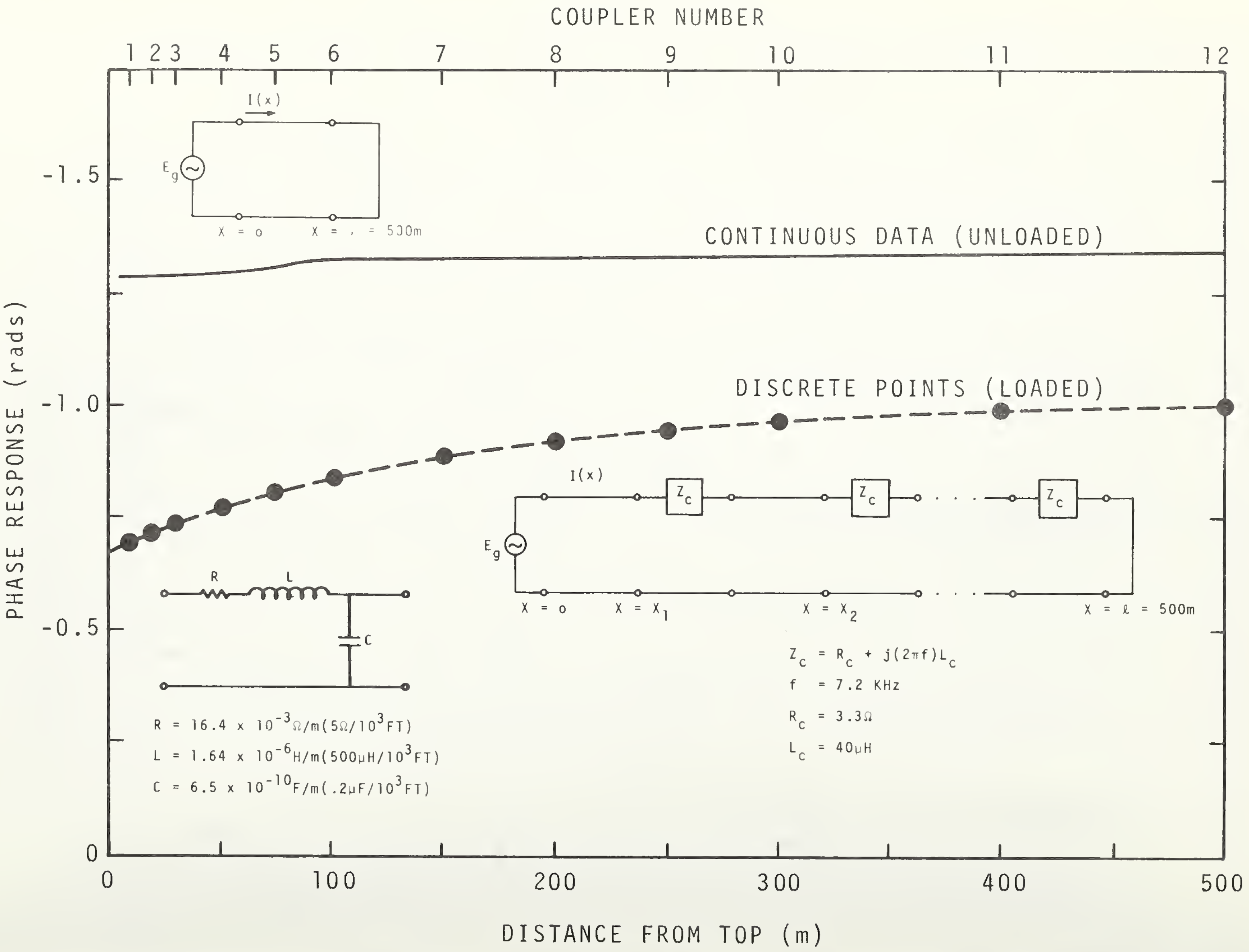

Figure 4.3 Current phase as function of position on loaded and unloaded line for 7.2 KHz sine wave.

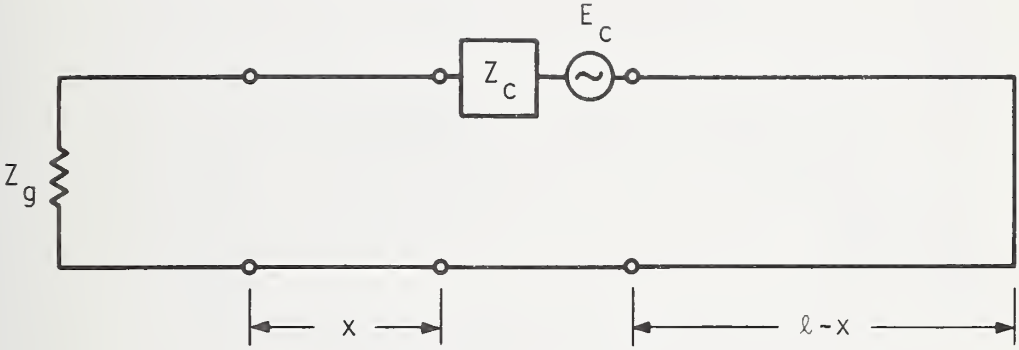

Figure 5. 1 Equivalent circuit of MLDL with coupler source down line.

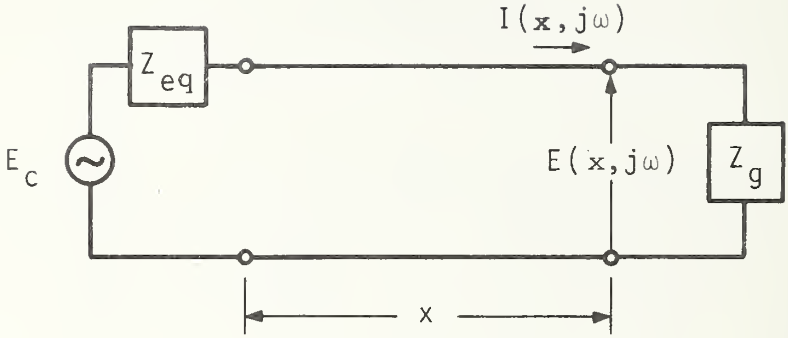

Figure 5.2 Thevenin equivalent of MLDL circuit model in Figure 5.1.

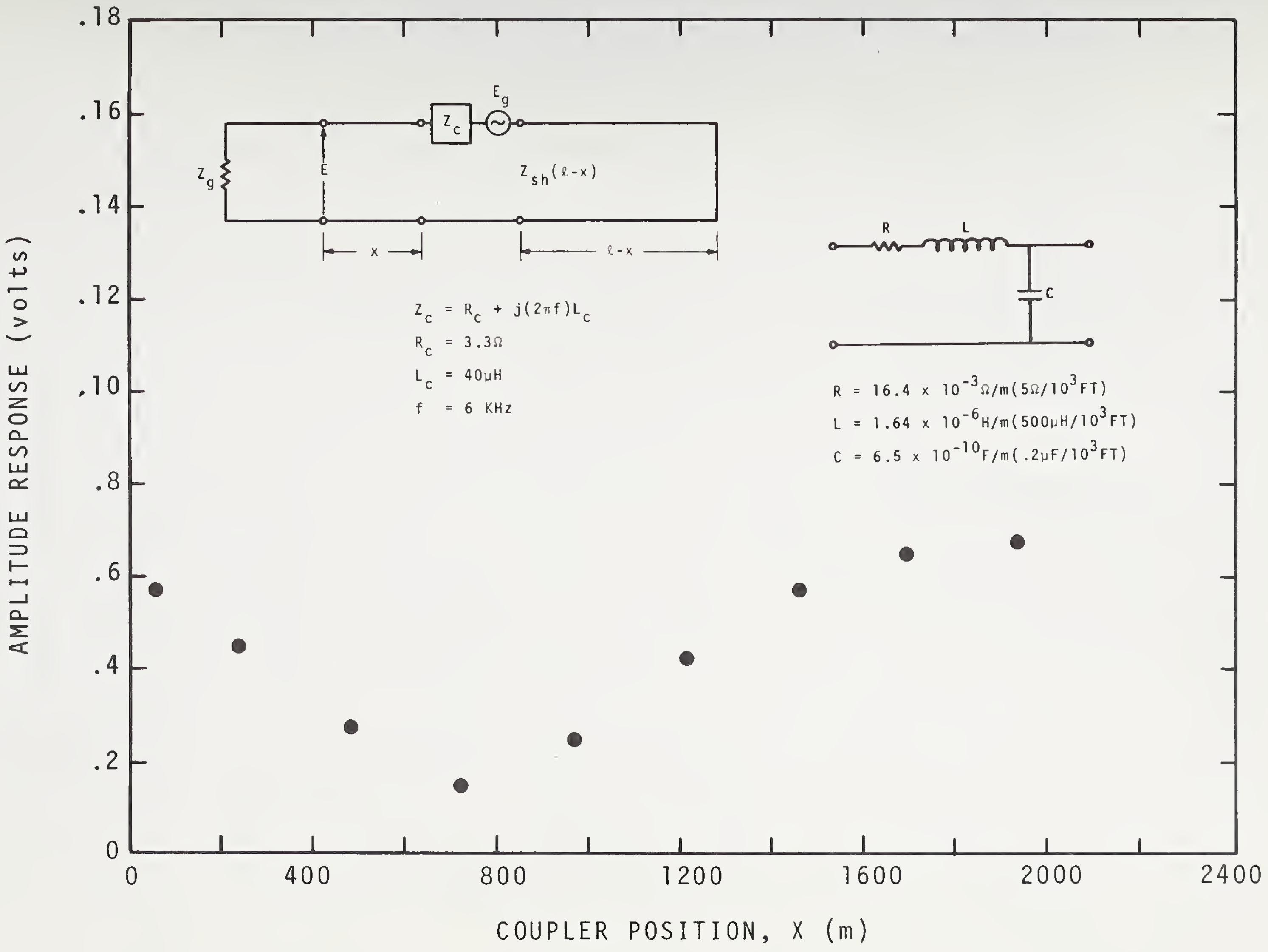

Figure 5.3 Received voltage amplitude versus discrete coupler positions upmode using 6 KHz coupler source.

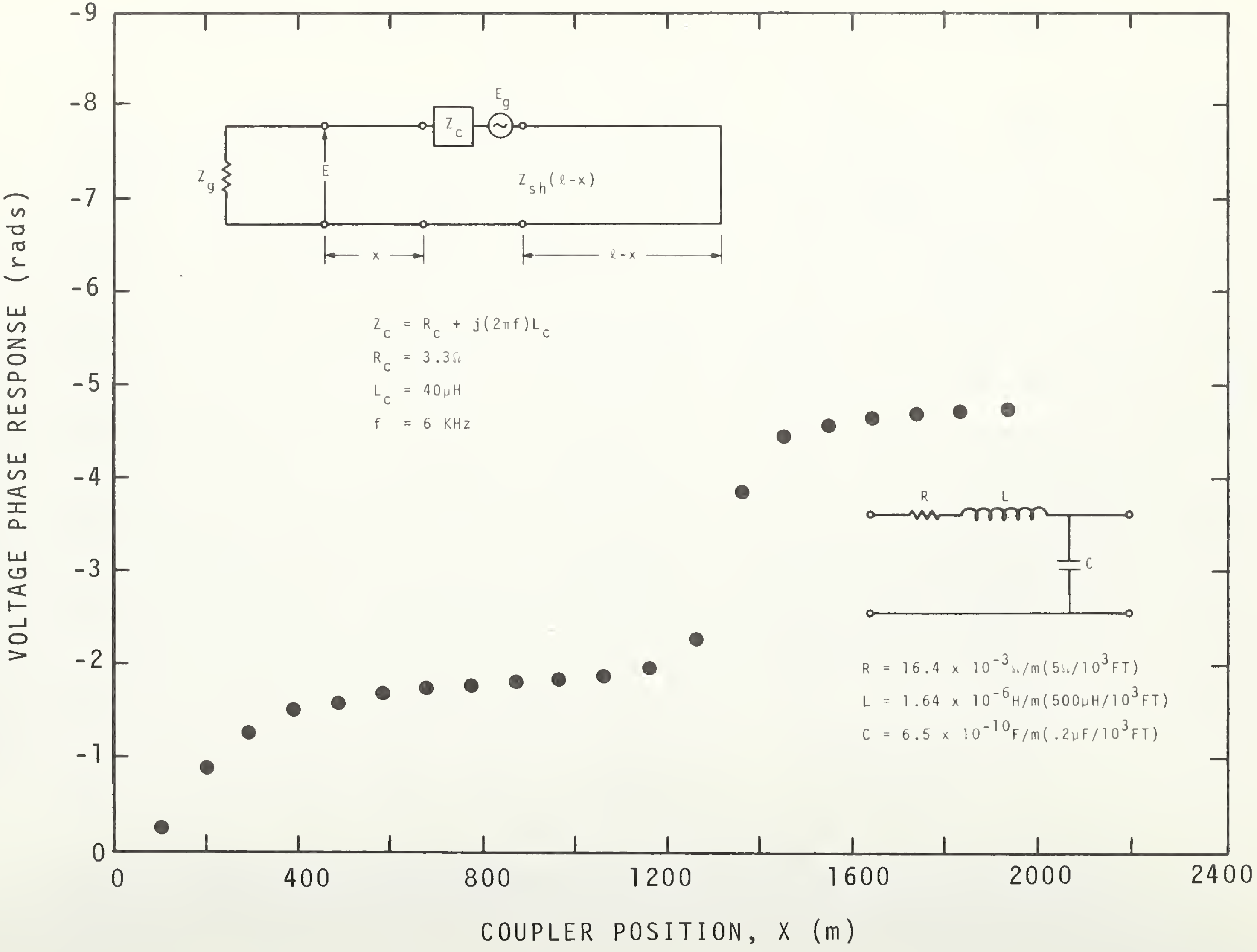

Figure 5.4 Received voltage phase versus discrete coupler positions upmode using 6 KHz coupler source.

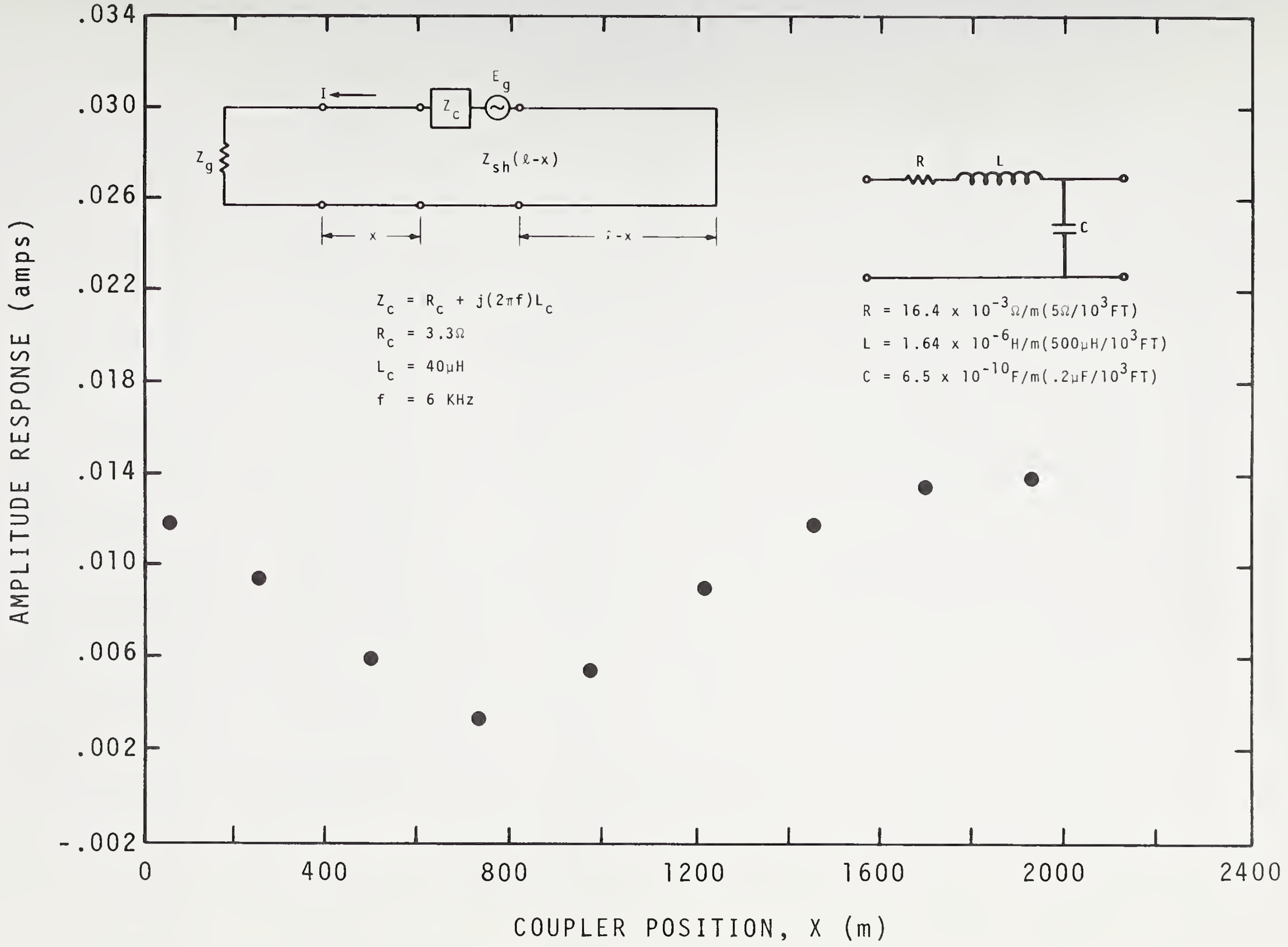

Figure 5.5 Received current amplitude versus discrete coupler positions upmode using 6 KHz coupler source.

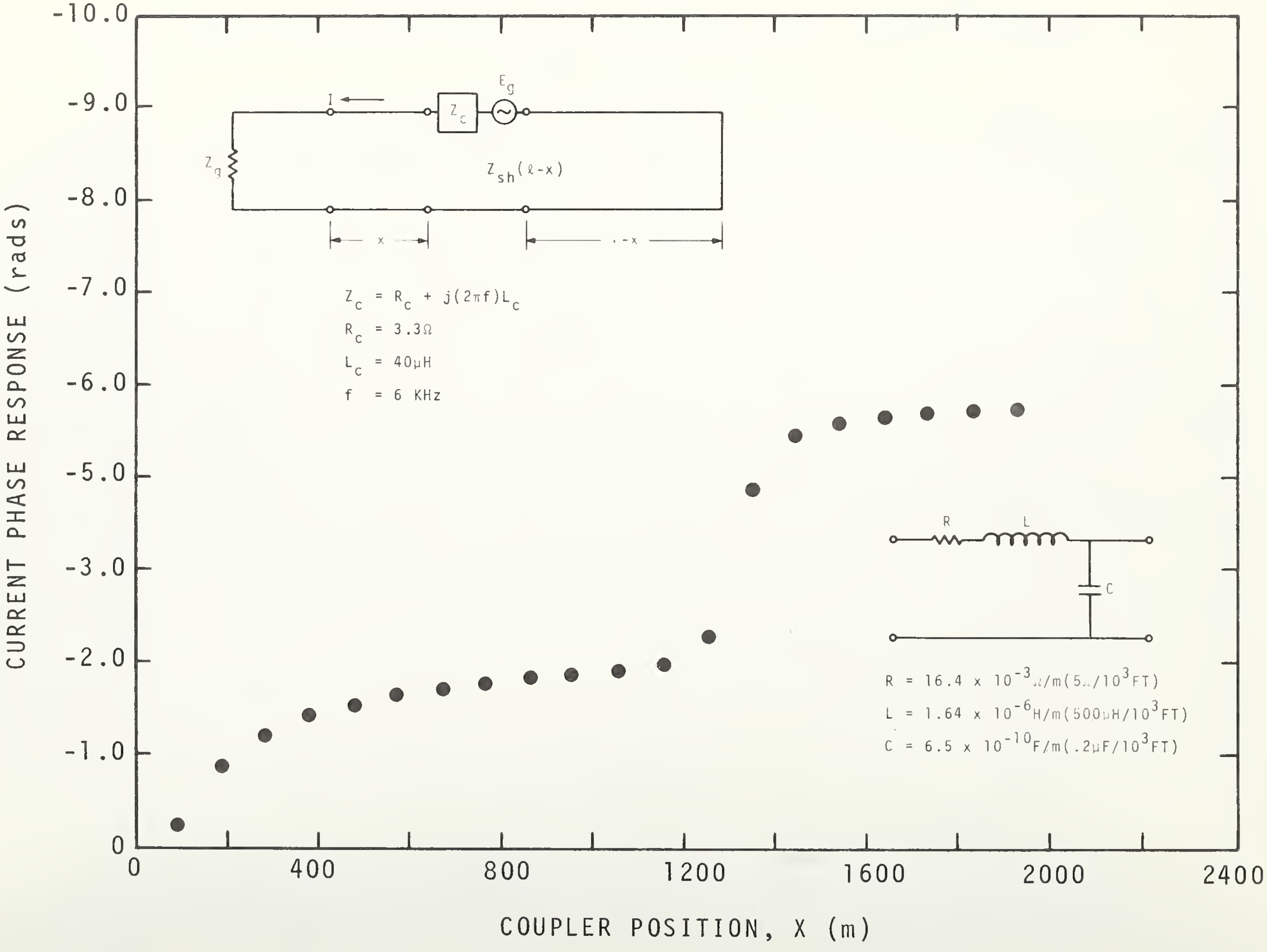

Figure 5.6 Received current phase versus discrete coupler positions upmode using 6 KHz coupler source.

APPENDIX

PROGRAM LISTINGS

A. 1 Program ZY

Program listing for computing series impedance (Z) and shunt admittance (Y) of the MLDL in Chapter 2, page 5.

```
      PROGRAM ZY
      DIMENSION F(2)
      TYPE COMPLEX Z,Y
      COMMON/BLOCK1/Z,Y
C-----------------------------------------------------------------------
C     COMPUTE SERIES IMPEDANCE(Z) AND SHUNT ADMITTANCE(Y) IN MKS UNITS
C-----------------------------------------------------------------------
      PRINT 220 $  PRINT 225  $  PRINT 230
      F(1)=1.E+3  $  F(2)=7.2*1.E+3
      DO 1 K=1,2
      CALL ZOGAM(F(K))
 1    PRINT 200,Z,Y,F(K)
      CALL EXIT
 200  FORMAT(28X,C(E12.5,E12.5),6X,C(E12.5,E12.5),11X,E8.2)
 220  FORMAT(57X,*SINGLE STRAND LINE PARAMETERS*//)
 225  FORMAT(36X,*SERIES IMPEDANCE(Z) AND SHUNT ADMITTANCE(Y) CALCULATIO
     1NS IN MKS UNITS*///)
 230  FORMAT(40X,*Z*,28X,*Y*,26X,*F*//30X,*OHMS/M*,7X,*OHMS/M*,23X,*MHOS
     1/M*,17X,*HZ*//)
      END
```

A. 2 Subroutines for ZOGAM

Version 1: Program listing for computing the characteristic impedance (Z_0) and propagation function (r) of the MLDL. (3. 1, page 6).

```
                                                          09/22/72
      SUBROUTINE Z0GAM(F,LSWCH)
      TYPE COMPLEX GAM10,S,Z0
      COMMON/BLOCK3/Z0,GAM10
      TYPE REAL L
C-----------------------------------------------------------------------
C     ALL PARAMETERS IN MKS UNITS
C     COMPUTE CHARACTERISTIC IMPEDANCE AND PROGATION FUNCTION OF LINE
C-----------------------------------------------------------------------
      IF(LSWCH.EQ.0)GO TO 1
      PI=3.14159  $  RTPI=SQRTF(PI)
      L=(.5*1.E-6)*3.28  $  C=(.2*1.E-9)*3.28
      R=(5.*1.E-3)*3.28
 1    S=(0.,1.)*F*2.*PI
      GAM10=CSQRT((L*S+R)*C*S)
      Z0=GAM10/(C*S)  $  RETURN  $  END
```

Version 2: Program listing for computing the characteristic impedance (Z_0) and propagation function (r) of the MLDL. (3. 1, page 6).

```
      SUBROUTINE Z0GAM(F)
      TYPE COMPLEX GAM10,S,ZA,ZB,Z0,Z,Y
      COMMON/BLOCK1/Z,Y
      COMMON/BLOCK3/Z0,GAM10
      TYPE REAL MU,L
C - ---------------------------     ----------------------------------
C     ALL PARAMETERS IN MKS UNITS
C-----------------------------------------------------------------------
      PI=3.14159  $  RTPI=SQRTF(PI)  $  MU=4.*PI*1.E-7
      B=.08/39.37  $  A=.055/39.37
      EPSR=2.3  $  EPS=EPSR*8.85*1.E-12
      L=MU/(2.*PI)*LOGF(B/A)  $  C=2.*PI*EPS/LOGF(B/A)
      GAM5=.57721  $  C0=1.7811  $  R0=SQRTF(L/C)
      ZA=(.0164,0.)  $  SIGMA2=5.
      ETA0=MU*SIGMA2*.25*(B**2)
 1    S=(0.,1.)*F*2.*PI
      ZB=-MU*S/(4.*PI)*(CLOG(C0*ETA0*S)+GAM5)
      GAM10=CSQRT(((L*S)+ZA+ZB)*C*S)
      Z=L*S+ZA+ZB  $  Y=C*S
      Z0=GAM10/(C*S)  $  RETURN  $  END
```

A. 3 Program RESPDATA

Program listing for computing attenuation, phase, input impedance and voltage amplitude of the MLDL in Chapter 3.

```
      PROGRAM RESPDATA
      DIMENSION ALPHA(1000),BETA(1000),ZNOT(1000),QTRLM(1000),REZ0(1000)
     1,FIMZ0(1000),RINSHRT(1000),XINSHRT(1000),RINOPEN(1000),XINOPEN(100
     20),AMPE0(1000),FREQ(2)
      TYPE COMPLEX Z0,GAM10,ZNOT,E50,ZINSHRT,ZINOPEN,EX,ELMX,AIX
      TYPE COMPLEX VOLTRESP,DNOM,S
      COMMON/BLOCK1/Z0,GAM10,R0,S
      COMMON/BLOCK2/PI,KPHAS
C-----------------------------------------------------------------------
C     ALL LINE PARAMETERS VALUES ARE FOUND IN SUBROUTINE ZOGAM
C     LS0 IS OPTION FOR COMPUTING ATTENUATION AND PHASE
C     LS1 IS OPTION FOR INPUT IMPEDANCE
C     LS2 IS OPTION FOR VOLTAGE AMPLITUDE
C     LP0 IS OPTION FOR PRINTING ATTENUATION AND PHASE
C     KFQ IS NUMBER OF FREQUENCY POINTS BETWEEN0 AND 10 KHZ
C-----------------------------------------------------------------------
      PI=3.14159
 100  FORMAT(4(4X,I1),5X,I5)
 22   READ 100,LS0,LS1,LS2,LP0,KFQ
      IF(EOF,60)45,46
 45   CALL EXIT
 46   KFQS=KFQ    $  PRINT 220 $  IF(LS0.EQ.0)GO TO 5
C-----------------------------------------------------------------------
C     COMPUTE ATTENUATION AND PHASE
C-----------------------------------------------------------------------
      DO 1 K=1,KFQ
      F=K*(1.E+4)/KFQS
      IF(K-2) 2,3,4
 2    LSWCH=1  $  GO TO 4
 3    LSWCH=0
 4    CALL Z0GAM(F,LSWCH)
      ALPHA(K)=REAL(GAM10)
      BETA(K) =AIMAG(GAM10)
      ZNOT(K) =Z0
      IF(BETA(K))32,34,32
 34   QTRLM(K)=1.E+100  $  GO TO 1
 32   QTRLM(K)=PI/(2.*BETA(K))
 1    CONTINUE
      IF(LP0.EQ.0)GO TO 5
      PRINT 200  $  KCNT=0
      DO 20 K=1,KFQ
      KCNT=KCNT+1
      IF(KCNT-46)36,37,37
 37   KCNT=1  $  PRINT 222  $  PRINT 200
 36   ALFDB=8.686*ALPHA(K)
      F=K*(1.E+4)/KFQS
 20   PRINT 202,F,ALFDB,BETA(K),QTRLM(K)
C-----------------------------------------------------------------------
C     COMPUTE INPUT IMPEDANCE OF LINE FOR SHORT,OPEN,AND Z0 TERMINATIONS
C-----------------------------------------------------------------------
 5    IF(LS1.EQ.0)GO TO 7
      DO 6 K=1,KFQ
      GAM10=ALPHA(K)+(0.,1.)*BETA(K)
      Z0=ZNOT(K)  $  E50=CEXP(-2.*500.*GAM10)
      ZINSHRT=Z0*(1.-E50)/(1.+E50)
```

```
      ZINOPEN=Z0*(1.+E50)/(1.-E50)
      REZ0(K)=REAL(Z0)   $   FIMZ0(K)=AIMAG(Z0)
      RINSHRT(K)=REAL(ZINSHRT)   $   XINSHRT(K)=AIMAG(ZINSHRT)
      RINOPEN(K)=REAL(ZINOPEN)   $   XINOPEN(K)=AIMAG(ZINOPEN)
 6    CONTINUE
      PRINT 220   $   KCNT=0   $   PRINT 204
      DO 24 K=1,KFQ
      KCNT=KCNT+1
      IF(KCNT-46)39,40,40
 40   KCNT=1   $   PRINT 222   $   PRINT 204
 39   F=K*(1.E+4)/KFQS
 24   PRINT 206,F,REZ0(K),FIMZ0(K),RINSHRT(K),XINSHRT(K),RINOPEN(K),
     1XINOPEN(K)
C-----------------------------------------------------------------------
C     COMPUTE VOLTAGE AMPLITUDE RESPONSE
C-----------------------------------------------------------------------
 7    IF(LS2.EQ.0)GO TO 22
      PRINT 222
      DO 10 K=1,KFQ
      GAM10=ALPHA(K)+(0.,1.)*BETA(K)
      Z0=ZNOT(K)   $   E50=CEXP(-2.*500.*GAM10)
      VOLTRESP=Z0/(Z0+50.)*(1.-E50)/(1.+E50)
 10   AMPE0(K)=CABS(VOLTRESP)
      KFPT=KFQ/3   $   FCTR=(1.E+4)/KFQS
      KFPT=KFPT*3   $   KCNT=0   $   PRINT 208
      DO 26 K=1,KFPT,3
      F1=K*FCTR   $   F2=FCTR+F1   $   F3=2.*FCTR+F1
      PRINT 210,F1,AMPE0(K),F2,AMPE0(K+1),F3,AMPE0(K+2)
      KCNT=KCNT+1   $   IF(KCNT-46)26,44,44
 44   KCNT=1   $   PRINT 222   $   PRINT 208
 26   CONTINUE
      GO TO 22
 200  FORMAT(25X,*F(HZ)*,14X,*ATTENUATION(DB/M)*,11X,*PHASE(RAD/M)*,10X,
     1*QUARTER WAVE LENGTH(M)*//)
 202  FORMAT(24X,E9.2,3(15X,E10.3))
 204  FORMAT(35X,*INPUT IMPEDANCE VERSUS FREQUENCY FOR 3 TERMINATING IMP
     1EDANCES*//29X,*Z0 TERMINATION*,14X,*SHORT TERMINATION*,13X,*OPEN
     2TERMINATION*///10X,*F(HERTZ)*,3(6X,*REAL(ZIN)*,6X,*IMAG(ZIN)*)/27X
     3,*OHMS*,5(11X,*OHMS*)///)
 206  FORMAT(11X,E8.2,6(6X,E10.3))
 208  FORMAT(16X,*SOURCE VOLTAGE AMPLITUDE RESPONSE USING SINE WAVE GENE
     1RATOR WITH 50 OHMS IMPEDANCE...CHARGING DOWN LINE*//12X,3(*F*,12X,
     2*AMPLITUDE RESPONSE*,7X)/10X,*(HZ)*,16X,*(VOLTS)*,12X,*(HZ)*,14X,
     3*(VOLTS)*,12X,*(HZ)*,15X,*(VOLTS)*//)
 210  FORMAT(3(8X,E9.2,11X,E10.3))
 220  FORMAT(1H1,17X,*SINGLE STRAND LINE PARAMETERS...R=5 OHMS/1000 FT
     1 L=500 MICROHENRYS/1000 FT   C=.2 MICROFARADS/1000 FT*//)
 222  FORMAT(1H1)
      END
```

A. 4 Program CURRESP

Program listing for computing current amplitude and phase of the unloaded MLDL in Chapter 3.

```
      PROGRAM CURRESP
      DIMENSION ABSIX2(1000),ABSIX3(1000),PHE2(1000),PHE3(1000)
      TYPE COMPLEX EX,ELMX,ELT
      TYPE COMPLEX Z0,GAM10,ZNOT,AIX1,AIX2,AIX3
      COMMON/BLOCK1/Z0,GAM10,R0
      COMMON/BLOCK2/PI,KPHAS2,KPHAS3
      PI=3.14159
C-----------------------------------------------------------------------
C     KX IS TOTAL NUMBER OF EQUIDISTANT POINTS ON LINE WHERE CURRENT
C     IS COMPUTED
C     XLT IS LENGTH OF LINE
C     F IS OPERATING FREQUENCY
C-----------------------------------------------------------------------
 100  FORMAT(5X,I5,4X,F6.1,3X,E7.1)
      READ 100,KX,XLT,F
      IF(EOF,60)45,46
 45   CALL EXIT
 46   CONTINUE
C-----------------------------------------------------------------------
C     COMPUTE AMPLITUDE AND PHASE OF CURRENT AS FUNCTION OF POSITION
C     ON LINE FOR Z0,OPEN,AND SHORT TERMINATIONS
C-----------------------------------------------------------------------
      LSWCH=1  $  CALL Z0GAM(F,LSWCH)  $  KPHAS2=KPHAS3=-1
      AIX1=1./Z0  $  ABSIX1=CABS(AIX1)  $  ANG1=CANG(AIX1)
      PRINT 220  $  DO 12 K=1,KX
      X10=K*XLT/KX  $  EX=CEXP(-1.*X10*GAM10)
      ELMX=CEXP(-(2.*XLT-X10)*GAM10)
      ELT=CEXP(-2.*XLT*GAM10)
      AIX2=1./Z0*(EX-ELMX)/(1.+ELT)
      AIX3=1./Z0*(EX+ELMX)/(1.-ELT)
      ABSIX2(K)=CABS(AIX2)  $  ABSIX3(K)=CABS(AIX3)
      ANG2=CANG(AIX2)  $  ANG3=CANG(AIX3)
      PHE2(K)=ANG2  $  PHE3(K)=ANG3
 12   CONTINUE
      LCNT=0  $  PRINT 200  $  PRINT 202      $  PRINT 203,F
      PRINT 204  $  PRINT 206  $  PRINT 208
      DO 10 K=1,KX
      X=K*XLT/KX  $  LCNT=LCNT+1
      IF(LCNT-46)13,14,14
 14   LCNT=0  $  PRINT 222  $  PRINT 206  $  PRINT 208
 13   PRINT 210,X,ABSIX2(K),PHE2(K),ABSIX3(K),PHE3(K)
 10   CONTINUE
      PRINT 207,ABSIX1,ANG1
 200  FORMAT(42X,F5.1,* KHZ SINE WAVE GENERATOR AT TOP CHARGING DOWN MOD
     1E*//)
 202  FORMAT(33X,*CURRENT RESPONSE AS FUNCTION OF POSITION ON LINE*,1X
     1,*FOR THREE DIFFERENT TERMINATIONS*//)
 203  FORMAT(52X,*OPERATING FREQUENCY IS*,E8.1,* HZ*//)
 204  FORMAT(42X,*ALL AMPLITUDE AND PHASE UNITS IN AMPERES AND RADIANS*/
     1/)
 206  FORMAT(26X,*DISTANCE FROM TOP*,13X,*OPEN TERMINATION*,16X,*SHORT T
     1ERMINATION*//)
 207  FORMAT (26X, *DISTANCE FROM TOP*, 15X, 1 * Z0 TERMINATION *111)
 208  FORMAT(32X,*METERS*,13X,2(*AMPLITUDE*,7X,*PHASE*,11X)//)
 209  FORMAT (32X, *METERS*, 13X, *AMPLITUDE*, 7X, *PHASE *11)
```

```
210  FORMAT(29X,F6.0,15X,2(E10.3,4X,E10.3,8X))
220  FORMAT(1H1,17X,*SINGLE STRAND LINE PARAMETERS...R=5 OHMS/1000 FT
    1 L=500 MICROHENRYS/1000 FT    C=.2 MICROFARADS/1000 FT*/)
222  FORMAT(1H1)
     END
```

A. 5 Program ALLCPLR

Program listing for computing current amplitude and phase of the loaded MLDL in Chapter 3.

```
      PROGRAM ALLCPLR
      DIMENSION R(50),L(50),DELX(50),T(50,10),U(50,10),V(50,10),W(50,10)
     1,A(10),B(10),C(10),D(10),DET5(10),ZNOT(10),GAM(10),E1(10),I1(10),
     2E2(10),ZC(50,10)
      DIMENSION I2(10),FREQ(10),X(51),FIABS(51,10),PHEI(51,10),ZIN(10),
     1I2X(51)
      COMMON/BLOCK1/A,B,C,D,DET,DET5,ZNOT,GAM,DELX
      COMMON/BLOCK2/T,U,V,W,ZC,NCPLR,NFRQ
      COMMON/BLOCK3/Z0,GAM10
      TYPE COMPLEX A,B,C,D,DET,DET5,ZNOT,GAM,T,U,V,W,E1,I1,E2,I2,ZC,ZIN,
     1I2X,Z0,GAM10
      TYPE REAL L
C-----------------------------------------------------------------------
C     MAXIMUM 50 COUPLERS AND 10 FREQUENCIES ARE ALLOWED
C     NCPLR STANDS FOR NO. OF COUPLERS
C     NFRQ STANDS FOR NO. OF DOWN MODE CHARGING FREQUENCIES
C     EACH COUPLER HAS A SERIES INDUCTANCE OF 40 MICRO HENRYS AND A
C     SERIES RESISTANCE OF 3.3 OHMS
C-----------------------------------------------------------------------
 100  FORMAT(5X,I5,5X,I5)
 102  FORMAT(16F5.1)
 104  FORMAT(8(4X,F6.1))
C-----------------------------------------------------------------------
C     COUPLER VALUES IN MKS UNITS
      DATA((L(I),I=1,50)=50(.00004))
      DATA((R(I),I=1,50)=50(3.3))
C-----------------------------------------------------------------------
 25   READ 100,NCPLR,NFRQ
      IF(EOF,60)45,46
 45   CALL EXIT
 46   READ 102,(DELX(I),I=1,NCPLR)
      IF(EOF,60)45,47
 47   READ 104,(FREQ(I),I=1,NFRQ)
      IF(EOF,60)45,48
 48   DO 11 J=1,NFRQ
      DO 18 K=1,NCPLR
 18   ZC(K,J)=R(K)+2.*3.14159*(0.,1.)*L(K)*FREQ(J)
 11   CONTINUE
      DO 1 J=1,NFRQ
      IF(J-2)23,19,22
 23   LSWCH=1  $  GO TO 22
 19   LSWCH=0
 22   CALL Z0GAM(FREQ(J),LSWCH)
      ZNOT(J)=Z0  $  GAM(J)=GAM10
 1    CONTINUE
      CALL ABCD  $  N50=NCPLR+1
      DO 3 J=1,NFRQ
      E2(J)=0.  $  E1(J)=1.
      I2(J)=E1(J)/B(J)  $  I1(J)=D(J)/B(J)*E1(J)
      DO 4 K=1,N50
      IF(K.EQ.1)GO TO 6
      K0=K-1
      CALL INVERT(K0,J)
      I2X(K)=D(J)*I2(J)  $  GO TO 5
 6    I2X(1)=I1(J)
```

```
5     FIABS(K,J)=CABS(I2X(K))  $  PHEI(K,J)=CANG(I2X(K))
4     CONTINUE
3     CONTINUE
      DO 20 K=1,N50
      IF(K.GT.1)GO TO 8
      X(1)=0.  $  GO TO 20
8     X(K)=X(K-1)+DELX(K-1)
20    CONTINUE
      DO 10 J=1,NFRQ
      F=FREQ(J)/(1.E+3)
      PRINT 204,NCPLR  $  PRINT 206  $  PRINT 212,F  $  PRINT 214
      PRINT 216  $  PRINT 218  $  PRINT 220  $  PRINT 222
      DO 12 K=1,N50
12    PRINT 202,X(K),FIABS(K,J),PHEI(K,J)
10    CONTINUE
      ZIN(1)=B(1)/D(1)  $  ZIN(2)=B(2)/D(2)
      DO 15 J=1,NFRQ
15    ZIN(J)=B(J)/D(J)
      PRINT 208
      DO 16 J=1,NFRQ
      F=FREQ(J)/(1.E+3)
16    PRINT 210,F,ZIN(J)
      GO TO 25
202  FORMAT(25X,F5.0,15X,E12.5,12X,E12.5//)
204  FORMAT(1H1,39X,*SINGLE STRAND LINE WITH *,I2,* COUPLERS*//)
206  FORMAT(39X,*DOWN MODE WITH GENERATOR AT SURFACE*////)
208  FORMAT(1H1,43X,*INPUT IMPEDANCE(ZIN)*//30X,*F(HZ)*,10X,*REAL(ZIN)*
    1,5X,*IMAG(ZIN)*///)
210  FORMAT(30X,E8.2,C(E16.3,E16.3))
212  FORMAT(27X,*GENERATOR CHARACTERISTICS...  EG=1 VOLT    ZG=50 OHMS
    1   F=*,F5.0,* KHZ*///)
214  FORMAT(35X,*THE FOLLOWING LINE PARAMETERS ARE USED---*///)
216  FORMAT(20X,*R=5 OHMS/1000 FT*,5X,*L=500 MICRO HENRYS/1000 FT*,5X,*
    1C=.2 MICRO FARADS/1000 FT*///)
218  FORMAT(25X,*THE FOLLOWING CURRENT RESPONSE IS COMPUTED AT EACH COU
    1PLER POSITION*///)
220  FORMAT(21X,*DISTANCE FROM TOP*,10X,*AMPLITUDE*,15X,*PHASE*)
222  FORMAT(25X,*(METERS)*,16X,*(AMPS)*,16X,*(RADIANS)*///)
      END
```

A. 6 Subroutine ABCD

```
      SUBROUTINE ABCD
      DIMENSION ZC(50,10),T(50,10),U(50,10),V(50,10),W(50,10),DELX(50),
     1A(10),B(10),C(10),D(10),DET5(10),ZNOT(10),GAM(10)
      COMMON/BLOCK1/A,B,C,D,DET,DET5,ZNOT,GAM,DELX
      COMMON/BLOCK2/T,U,V,W,ZC,NCPLR,NFRQ
      TYPE COMPLEX ZC,Z0,GAM10,E50,A0,B0,C0,D0,A1,B1,C1,D1,A2,B2,C2,D2,
     1A3,B3,C3,D3,A4,B4,C4,D4,DET,DET5,T,U,V,W,A,B,C,D,ZNOT,GAM
C     ------------------------------------------------------------------
C     CALCULATE OVERALL ABCD PARAMETERS OF COMPLETELY LOADED LINE
C     COUPLER IMPEDANCE IS ZC
C     T,U,V,W ARE THE INVERSE MATRIX ELEMENTS IN POSITIONS (1,1),(1,2),
C     (2,1),(2,2) RESPECTIVELY AND THEY ARE DEFINED IN THE REPORT ON
C     PAGE
C     ------------------------------------------------------------------
      DO 1 J=1,NFRQ
      A3=D3=1.  $  B3=C3=0.
      GAM10=GAM(J)  $  Z0=ZNOT(J)
      DO 2 K=1,NCPLR
 5    E50=CEXP(DELX(K)*GAM10)  $  A0=(E50+1./E50)/2.
      B0=ZC*(E50-1./E50)/2.  $  C0=B0/(Z0**2)  $  D0=A0
      A1=1.  $  B1=ZC(K,J)  $  C1=0.  $  D1=1.
      A2=A0*A1+B0*C1  $  B2=A0*B1+B0*D1
      C2=C0*A1+D0*C1  $  D2=C0*B1+D0*D1
      A4=A3*A2+B3*C2  $  B4=A3*B2+B3*D2
      C4=C3*A2+D3*C2  $  D4=C3*B2+D3*D2
      A3=A4  $B3=B4  $C3=C4  $  D3=D4
      DET=A0*D0-B0*C0
      T(K,J)=(D0+C0*ZC(K,J))/DET  $  U(K,J)=-(B0+A0*ZC(K,J))/DET
      V(K,J)=-C0/DET  $  W(K,J)=A0/DET
 2    CONTINUE
      A(J)=A3  $  B(J)=B3  $  C(J)=C3  $  D(J)=D3
 1    DET5(J)=A3*D3-C3*B3
      RETURN  $  END
```

```
 SUBROUTINE INVERT(K,J)
 DIMENSION T(50,10),U(50,10),V(50,10),W(50,10),A(10),B(10),C(10),
1D(10)
 COMMON/BLOCK1/A,B,C,D,DET,DET5,ZNOT,GAM,DELX
 COMMON/BLOCK2/T,U,V,W,ZC,NCPLR,NFRQ
 TYPE COMPLEX T,U,V,W,A,B,C,D,A0,B0,C0,D0
 A0=T(K,J)*A(J)+U(K,J)*C(J)
 B0=T(K,J)*B(J)+U(K,J)*D(J)
 C0=V(K,J)*A(J)+W(K,J)*C(J)
 D0=V(K,J)*B(J)+W(K,J)*D(J)
 A(J)=A0  $  B(J)=B0  $  C(J)=C0  $  D(J)=D0
 RETURN  $  END
```

A.7 Program UPMODE

Program listing for computing the upmode voltage and current response of the MLDL in Chapter 5.

```
       PROGRAM UPMODE
       DIMENSION FREQ(25),XPOS(50),GAM(25),ZNOT(25),ZC(25),RHOG(25),FI2
      1(50,25),E2(50,25)
       TYPE COMPLEX GAM10,Z0,GAM,ZNOT,ZC,RHOG,ZSH,ZCAPC,EX,RHOC,FI2,E2
       COMMON/BLOCK3/Z0,GAM10
       TYPE REAL LC
C-----------------------------------------------------------------------
C      COMPUTE VOLTAGE AND CURRENT RESPONSE IN UPMODE
C      FOLLOWING LINE PARAMETERS ARE USED
C      R=5 OHMS/1000 FT   C=.2 MICROFARADS/1000 FT   L=500 MICROHENRYS
C      /1000 FT
C      FOLLOWING COUPLER PARAMETERS ARE USED
C      R=3.3 OHMS    L=40 MICROHENRYS
C-----------------------------------------------------------------------
       RC=3.3  $  LC=.00004  $  PI=3.14159  $  ZG=50.
 100   FORMAT(2(5X,I5),F5.1)
 102   FORMAT(8(4X,E6.1))
 104   FORMAT(16F5.1)
18     READ 100,NFRQ,NPOS,X50
       IF(EOF,60)45,46
 45    CALL EXIT
 46    READ 102,(FREQ(I),I=1,NFRQ)
       IF(EOF,60)45,47
 47    READ 104,(XPOS(I),I=1,NPOS)
       IF(EOF,60)45,48
 48    CONTINUE
C-----------------------------------------------------------------------
C      THE FOLLOWING PROGRAM PARAMETERS ARE EXPLAINED
C      NFRQ IS TOTAL NUMBER OF CHARGING FREQUENCIES
C      NPOS IS NUMBER OF GENERATOR POSITIONS DOWN LINE
C      X50 IS OVERALL LINE LENGTH
C-----------------------------------------------------------------------
       DO 1 J=1,NFRQ
       F=FREQ(J)
       IF(J-2)2,3,4
 2     LSWCH=1  $  GO TO 4
 3     LSWCH=0
 4     CALL Z0GAM(F,LSWCH)
       GAM(J)=GAM10  $  ZNOT(J)=Z0
       ZC(J)=RC+LC*(0.,1.)*F*2.*PI
 1     RHOG(J)=(ZG-Z0)/(ZG+Z0)
       EC=1.
       DO 5 K=1,NPOS
       X=XPOS(K)
       DO 6 J=1,NFRQ
       ZSH=Z0*(1.-CEXP(-2.*(X50-X)*GAM(J)))/(1.+CEXP(-2.*(X50-X)*GAM(J)))
       ZCAPC=ZC(J)+ZSH  $  EX=CEXP(-X*GAM(J))
       RHOC=(ZCAPC-ZNOT(J))/(ZCAPC+ZNOT(J))
       FI2(K,J)=EC*EX/(ZNOT(J)+ZCAPC)*((1.-RHOG(J))/(1.-RHOC*RHOG(J)*(EX
      1**2)))
       E2(K,J)=EC*ZNOT(J)/(ZNOT(J)+ZCAPC)*EX*((1.+RHOG(J))/(1.-RHOC*RHOG
      1(J)*(EX**2)))
 6     CONTINUE
 5     CONTINUE
       DO 10 J=1,NFRQ
```

```
      F=FREQ(J)/(1.E+3)
      PRINT 204  $  PRINT 206,F  $  PRINT 214
      PRINT 216  $  PRINT 218  $  PRINT 220  $  PRINT 222
      DO 12 K=1,NPOS
      FIABS=CABS(FI2(K,J))  $  PHEI=CANG(FI2(K,J))
 12   PRINT 202,XPOS(K),FIABS,PHEI
      PRINT 224  $  PRINT 220  $  PRINT 226
      DO 16 K=1,NPOS
      E2ABS=CABS(E2(K,J))  $  PHE2=CANG(E2(K,J))
 16   PRINT 202,XPOS(K),E2ABS,PHE2
 10   CONTINUE
      GO TO 18
 202  FORMAT(26X,F5.0,15X,E12.5,12X,E12.5//)
 204  FORMAT(1H1,39X,*SINGLE STRAND LINE WITH 1 COUPLER*///)
 206  FORMAT(39X,*UPMODE USING 1 VOLT*,F5.0,* KHZ SOURCE*///)
 208  FORMAT(1H1,43X,*INPUT IMPEDANCE(ZIN)*//35X,*F(HZ)*,10X,*REAL(ZIN)*
     1,5X,*IMAG(ZIN)*///)
 210  FORMAT(30X,E8.2,C(E16.3,E16.3))
 212  FORMAT(30X,*GENERATOR CHARACTERISTICS...  EG=1 VOLT  F=*,F5.0,* KH
     1Z*///)
 214  FORMAT(35X,*THE FOLLOWING LINE PARAMETERS ARE USED---*///)
 216  FORMAT(25X,*R=5 OHMS/1000 FT*,5X,*L=500 MICRO HENRYS/1000 FT*,5X,*
     1C=.2 MICRO FARADS/1000 FT*///)
 218  FORMAT(9X,*THE FOLLOWING CURRENT RESPONSE IS AT SURFACE AS FUNCTIO
     1N OF DISTANCE FROM COUPLER SOURCE*///)
 220  FORMAT(21X,*DISTANCE FROM TOP*,15X,*AMPLITUDE*,15X,*PHASE*)
 222  FORMAT(25X,*(METERS)*,16X,*(AMPS)*,16X,*(RADIANS)*///)
 224  FORMAT(9X,*THE FOLLOWING VOLTAGE RESPONSE IS AT SURFACE AS FUNCTIO
     1N OF DISTANCE FROM COUPLER SOURCE*///)
 226  FORMAT(25X,*(METERS)*,16X,*(VOLTS)*,15X,*(RADIANS)*///)
      END
```

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Equations and computer programs are presented for calculating the propagation properties of the Mooring Line Data Line (MLDL). The development is based upon a single-strand inner conductor model for the MLDL structure. Propagation parameters, input impedance, voltage amplitude, and current are developed from the complex impedance/meter (Z) and the complex admittance/meter (Y) of the MLDL. A matrix formulation of the voltages and currents along an MLDL loaded with couplers at arbitrary positions is developed. The received voltage and current at the water surface produced by a single coupler down line at an arbitrary distance are presented.

17. KEY WORDS (Alphabetical order, separated by semicolons) attenuation; characteristic impedance; circuit model; computer printout; computer program; coupler; current; impedance; load impedance; mooring line data line; phase; propagation characteristics; sea water return; series impedance; shunt admittance; single strand; transmission line

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