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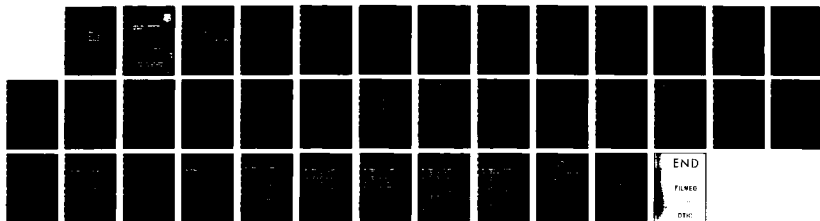
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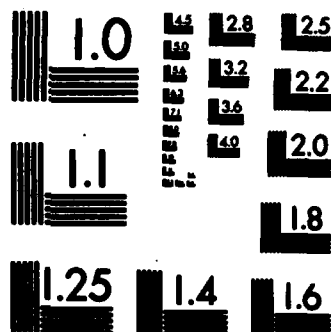
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RADC-TR-84-148
In-House Report
June 1984



LUMPED CIRCUIT TRANSMISSION LINE MODEL

Douglas H. Colvin

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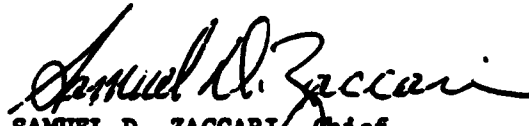
ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441

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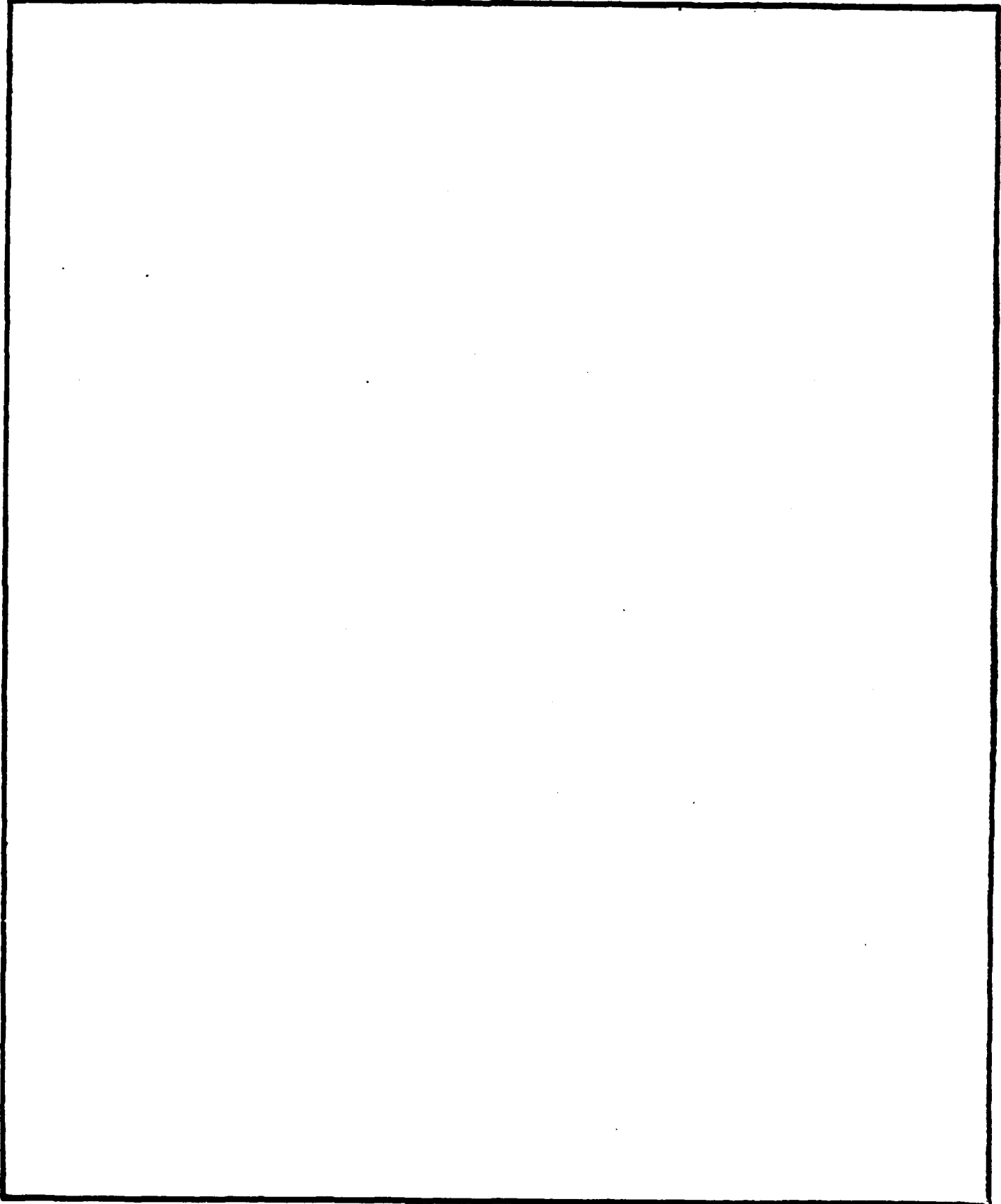
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Lumped Circuit Transmission Line Model

INTRODUCTION

Several computer aided design (CAD) programs require lumped circuit component values (resistors, inductors, and capacitors) as input data. It is often difficult, if not impossible, for a user of these CAD programs to mix distributed and lumped circuit parameters. Lumped circuit equivalents of distributed circuits are desired for sake of compatibility.

Transmission line responses are governed by distributed parameters. In this report, the development of a lumped circuit model for the lossless transmission line is performed by deriving its Z-parameter expressions and then synthesizing these parameters with lumped circuit equivalents.

If the Z-parameters are accurately synthesized, the model will be virtually insensitive to source or load impedances. Two forms of Z-parameter networks are possible: the "T" network and the "II" network. In this report, the "T" network is employed.

THE DISTRIBUTED PARAMETER TRANSMISSION LINE (DPTL)

This section describes the necessary equations needed to work with the lossless DPTL. The dominant mode for the propagation of signals is assumed to be transverse electromagnetic (TEM) in which both the electric and magnetic fields are transverse (perpendicular) to the axis of the transmission line. Also, the DPTL is assumed to be uniform and the medium of propagation is

assumed to be homogeneous.

Voltages and currents at any point along the line can be determined if the total voltage and current are known at the sending and receiving ends of that line. Corresponding to Figure 1, we have (1)

$$\begin{aligned}V_S &= V_R \cosh \gamma l + I_R Z_0 \sinh \gamma l \\V_R &= V_S \cosh \gamma l - I_S Z_0 \sinh \gamma l \\I_S &= I_R \cosh \gamma l + (V_R / Z_0) \sinh \gamma l \\I_R &= I_S \cosh \gamma l - (V_S / Z_0) \sinh \gamma l\end{aligned}\quad (1)$$

where, Z_0 = characteristic impedance

γ = propagation constant

and other quantities are defined in Figure 1.

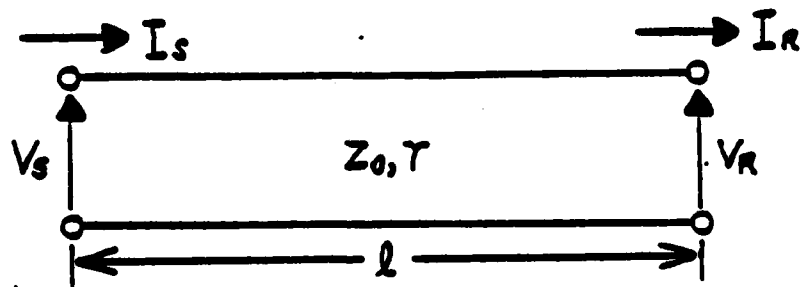


Figure 1

The characteristic impedance and propagation constant are typically expressed as

$$Z_0 = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \quad \gamma = \sqrt{(R+j\omega L)(G+j\omega C)} \quad (2)$$

where, R = resistance per unit length

L = inductance per unit length

G = conductance per unit length

C = capacitance per unit length

If R and G are assumed to be negligible, as for the lossless line, equation (2) becomes

$$Z_0 = \sqrt{\frac{L}{C}} \quad , \quad \gamma = j\omega \sqrt{LC} \quad \beta \quad j\beta \quad (3)$$

and substitution into equation (1) yields

$$\begin{aligned} V_S &= V_R \cos \beta l + jI_R Z_0 \sin \beta l \\ V_R &= V_S \cos \beta l - jI_S Z_0 \sin \beta l \\ I_S &= I_R \cos \beta l + j(V_R/Z_0) \sin \beta l \\ I_R &= I_S \cos \beta l - j(V_S/Z_0) \sin \beta l \end{aligned} \quad (4)$$

The equations in (4) are the only ones required to find the Z parameters of the lossless DPTL.

Z-PARAMETERS FOR THE LOSSLESS OPTL

The symmetric and reciprocal OPTL may be fully described by a "T" network incorporating the Z-parameters shown in Figure 2.

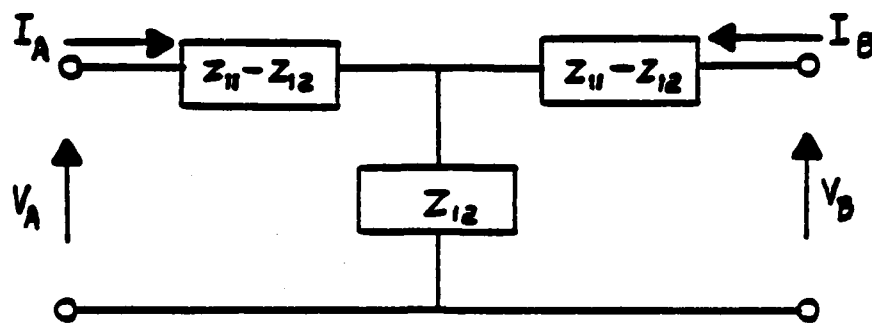


Figure 2

The input and output voltages are determined from

$$V_A = Z_{11} I_A + Z_{12} I_B$$

$$V_B = Z_{21} I_A + Z_{22} I_B \quad (5)$$

Since we have symmetry and reciprocity, $Z_{21} = Z_{12}$ and $Z_{22} = Z_{11}$ so that (5) becomes

$$\begin{aligned} V_A &= Z_{11} I_A + Z_{12} I_B \\ V_B &= Z_{12} I_A + Z_{11} I_B \end{aligned} \quad (6)$$

The equations in (4) may be manipulated so that V_S and V_R are in terms of I_S and I_R . Upon doing this, we have

$$\begin{aligned} V_S &= -jI_S Z_0 \cot \beta l + jI_R Z_0 \csc \beta l \\ V_R &= -jI_S Z_0 \csc \beta l + jI_R Z_0 \cot \beta l \end{aligned} \quad (7)$$

When these equations for V_S and V_R are compared to the equations in (6), we can see that we have the relationships between the Z-parameters and the DPTL parameters:

$$\begin{aligned} Z_{11} &= -jZ_0 \cot \beta l, \quad Z_{12} = -jZ_0 \csc \beta l \\ \text{and } Z_{11} - Z_{12} &= jZ_0 \tan \beta l / 2 \end{aligned}$$

The DPTL may now be represented by the network shown in Figure 3.

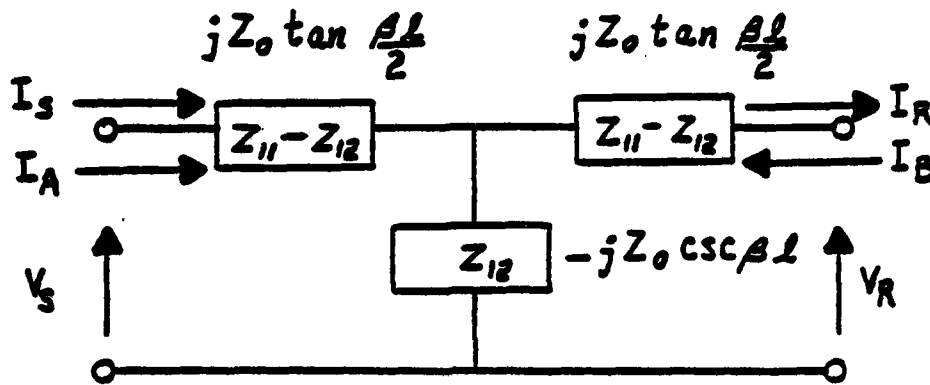


Figure 3

The remaining task is to find circuits which will represent the impedances $jZ_0 \tan \beta l / 2$ and $-jZ_0 \csc \beta l$ to a high degree of accuracy. The techniques used are discussed in the next section.

CIRCUIT SYNTHESIS

The impedances, $Z_{11} - Z_{12}$ and Z_{12} , will be synthesized separately. Since these impedances are trigonometric functions, it is suitable to express the sine and cosine in terms of polynomial expansions. (2)

$$\sin X = X (1 + a_2 X^2 + a_4 X^4 + a_6 X^6 + a_8 X^8 + a_{10} X^{10}) + |\epsilon_a|$$

$$|\epsilon_a| \leq 2 \times 10^{-9}, \quad 0 \leq X \leq \pi/2$$

$$\cos X = 1 + b_2 X^2 + b_4 X^4 + b_6 X^6 + b_8 X^8 + b_{10} X^{10} + |\epsilon_b|$$

$$|\epsilon_b| \leq 2 \times 10^{-9}, \quad 0 \leq X \leq \pi/2 \quad (8)$$

$$\csc X = \frac{1}{X} + 2X \sum_{n=1}^{\infty} \frac{(-1)^n}{X^2 - (n\pi)^2} \quad (9)$$

where:

$$a_2 = -.1666666664$$

$$b_2 = -.4999999963$$

$$a_4 = .0083333315$$

$$b_4 = .0416666413$$

$$a_6 = -.0001984090$$

$$b_6 = -.0013888397$$

$$a_8 = .0000027526$$

$$b_8 = .0000247609$$

$$a_{10} = -.0000000239$$

$$b_{10} = -.0000002605$$

Equations in (8) are used for $jZ_0 \tan \beta l / 2$, and equation (9) is used for $-jZ_0 \csc \beta l$. First, we will synthesize the impedance, $jZ_0 \tan \beta l / 2$, then we will work on $jZ_0 \csc \beta l$.

SYNTHESIS OF $Z_{11} - Z_{12}$

It can be shown that $\beta l / 2 = -jKs$ where $K = \frac{2\sqrt{\mu\epsilon}}{c}$ and $s = j\omega$. Now we may write $jZ_0 \tan \beta l / 2$ as $jZ_0 \tan (-jKs)$.² Using equations in (8), we get:

$$jZ_0 \tan(-jKs) = jZ_0 \left[\frac{-jKs \{1 + a_2(-jKs)^2 + a_4(-jKs)^4 + \dots + a_{10}(-jKs)^{10}\}}{1 + b_2(-jKs)^2 + b_4(-jKs)^4 + \dots + b_{10}(-jKs)^{10}} \right]$$

$$= \frac{Z_0 K s - a_2 Z_0 K^3 s^3 + a_4 Z_0 K^5 s^5 - a_6 Z_0 K^7 s^7 + a_8 Z_0 K^9 s^9 - a_{10} Z_0 K^{11} s^{11}}{1 - b_2 K^2 s^2 + b_4 K^4 s^4 - b_6 K^6 s^6 + b_8 K^8 s^8 - b_{10} K^{10} s^{10}}$$

(10)

$$\Delta = \frac{N(s)}{D(s)}$$

Synthetic division of (10) is performed in a manner shown in equation (11) which yields a network of a Cauer form (Figure 4). See Appendix A.

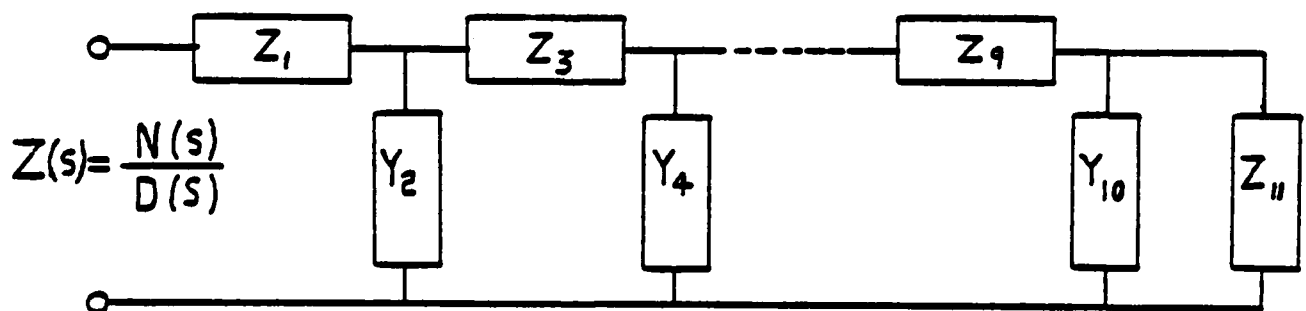


Figure 4

$$\frac{N(s)}{D(s)} = \frac{Z_1}{Y_2 + \frac{1}{Z_3 + \frac{1}{Y_4 + \frac{1}{\dots}}}} \quad (11)$$

Once the synthetic division is complete, we can find the corresponding circuit elements.

$$L_1 = .09174664Z_0K$$

$$C_2 = .5417253K/Z_0$$

$$L_3 = -.03511307Z_0K$$

$$C_4 = -.04033142K/Z_0$$

$$L_5 = .07935383Z_0K$$

$$C_6 = .2536086K/Z_0$$

$$L_7 = .7765806Z_0K$$

$$C_8 = -.05267314K/Z_0$$

$$L_9 = -.2371512Z_0K$$

$$C_{10} = .5358672K/Z_0$$

$$L_{11} = .3245832Z_0K$$

where L is in Henrys and C is in Farads.

Figure 5 shows the completed circuit whose port impedance is $jZ_0 \tan \beta l / 2$.

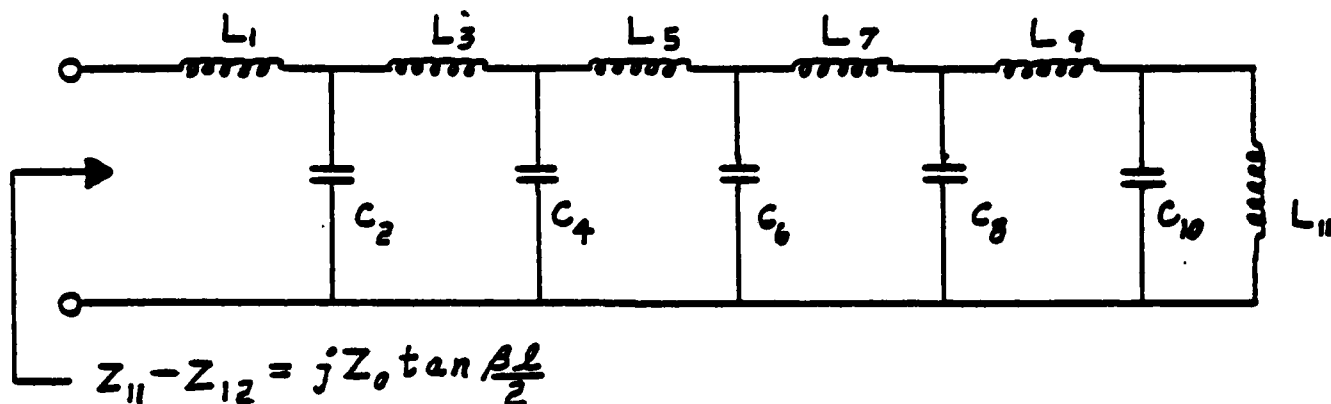


Figure 5

SYNTHESIS OF Z_{12}

For the synthesis of $Z_{12} = -jZ_0 \csc \beta l$, we use the expansion form of equation (9) but instead of an infinite summation, we will use N terms. Letting $x = \beta l = -j2Ks$, we get

$$-jZ_0 \csc \beta l = -jZ_0 \left[\frac{1}{-j2Ks} + 2(-j2Ks) \sum_{n=1}^N \frac{(-1)^n}{(-j2Ks)^2 - (n\pi)^2} \right]$$

which may be rearranged into

$$-jZ_0 \csc \beta l = \frac{Z_0}{2Ks} + \sum_{n=1}^N \frac{(-1)^n 4Z_0 Ks}{4K^2 s^2 + (n\pi)^2} \quad (12)$$

The addend of equation (12) is of the form $\frac{as}{bs^2+c}$ which is a

general impedance expression of an LC tank circuit.

Consider the tank circuit of Figure 6; its terminal impedance is given by

$$Z(s) = \frac{sL}{LCs^2+1}$$

which can be forced to equal the addend of (12). By doing this we find that

$$L_n = \frac{(-1)^n 4Z_0 K}{(n\pi)^2}, \quad C_n = \frac{K}{(-1)^n Z_0}$$

The first term of (12) is the impedance of a capacitor whose value is $2K/Z_0$. Now the synthesized circuit for Z_{12} is complete and shown in Figure 7.

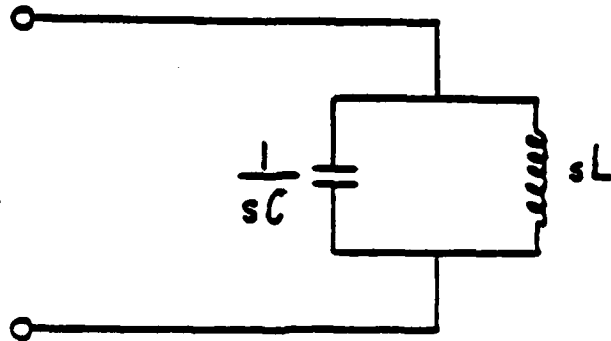


Figure 6

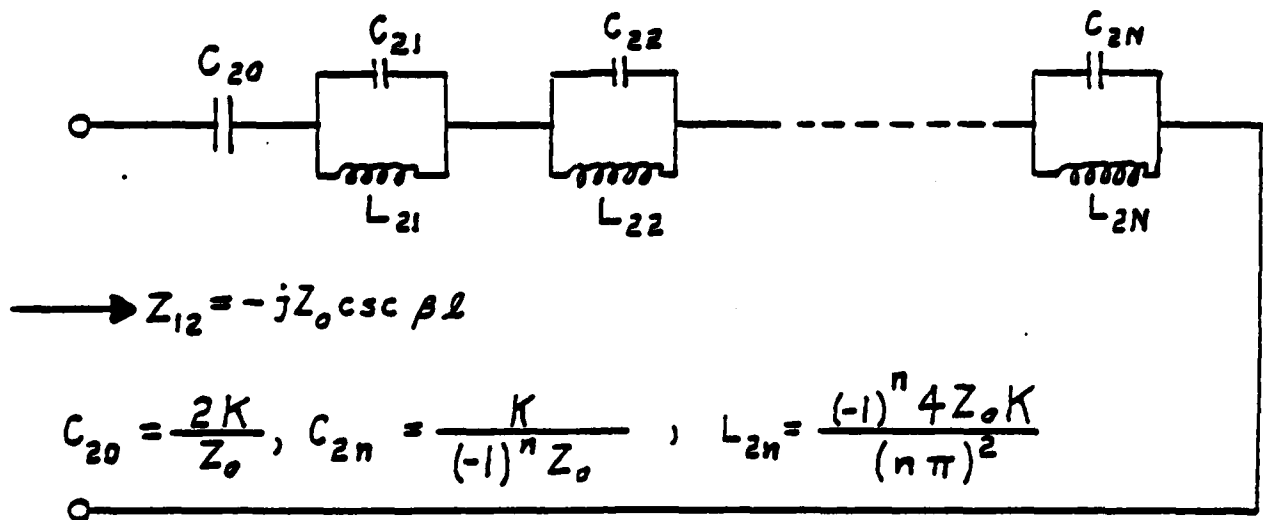


Figure 7

THE COMPLETED MODEL AND ITS ANALYSIS

By placing the networks of Figure 5 and Figure 7 into the Z-parameter network of Figure 2, the complete model for the DPTL is developed. Shown in Figure 8 is the model's schematic along with the source and load impedances.

A Fortran Program (Appendix B) has been written in order that the DPTL model may be analyzed for errors in the output voltage. In the program, "MVOD" is the magnitude of V_S/V_L (See Figure 8) as determined by the use of the standard transmission line equations and "MVOL" is the magnitude of V_S/V_L as determined by the DPTL model. The error (in dB) (See Figure 9) is defined as

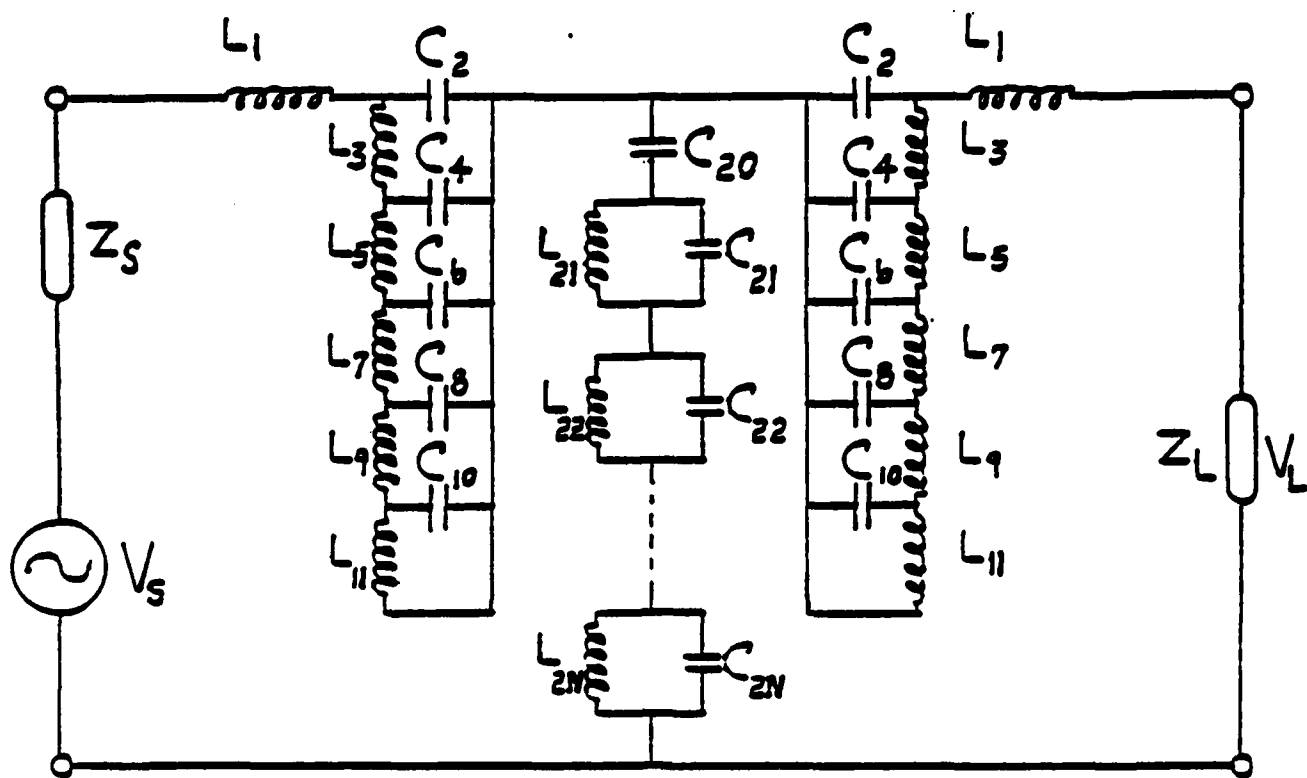
$$\text{Error}_{\text{dB}} = 20 \text{ Log (MVOL/MVOD)}$$

Resonances along the line are very evident. The errors at $\lambda/4$ and $3\lambda/4$ are seen to be small compared to those at $\lambda/2$ and λ . This is because the approximations of equation (8) are in greatest error at $x = \pi/2$ and least error at $x=0$ and $x=\pi/4$. The huge error at line lengths of $\lambda/2$ and λ are not troublesome if one does not include frequencies which correspond to line lengths equal to exactly $\lambda/2$ and λ .

Conclusion and Recommendations

The sample runs in Appendix B are for transmission lines with

LOSSLESS DPTL MODEL



$$\begin{aligned}
 L_1 &= .04587332KZ_0 \\
 L_3 &= -.01755653KZ_0 \\
 L_5 &= .03967702KZ_0 \\
 L_7 &= .38828470KZ_0 \\
 L_9 &= -.11857035KZ_0 \\
 L_{11} &= .16229000KZ_0
 \end{aligned}$$

$$\begin{aligned}
 C_{20} &= 2K/Z_0 \\
 C_2 &= .27086255K/Z_0 \\
 C_4 &= -.020165705K/Z_0 \\
 C_6 &= .12680405K/Z_0 \\
 C_8 &= -.02633792K/Z_0 \\
 C_{10} &= .26795260K/Z_0
 \end{aligned}$$

$$L_{2n} = (-1)^n \frac{2KZ_0}{(n\pi)^2}$$

$$C_{2n} = (-1)^n \frac{K}{2Z_0}$$

$$K = \frac{\beta l}{\omega}$$

Figure 8

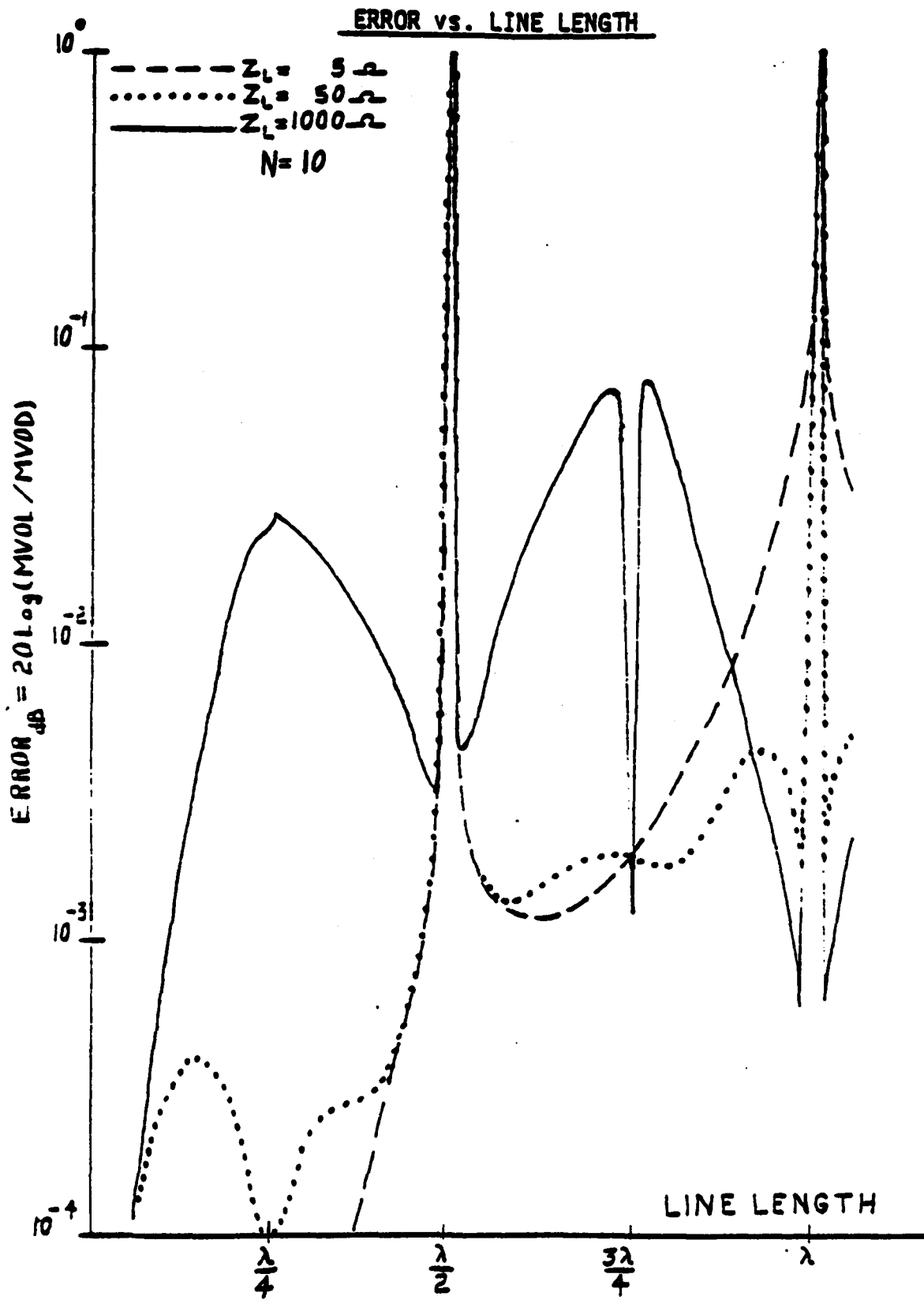


Figure 9

relative permittivity (ϵ_r) equal to one. The program allows one to input other values of ϵ_r ; but then, the effective line length will be different.

The errors between calculations from the DPTL model and the transmission line equations are less than one-tenth decibel provided the effective line length is less than or equal to one wavelength. The load, Z_L , does not significantly affect the results unlike the case of typical lumped circuit models (4).

The use of the DPTL model may be found for several applications where line losses are low. When losses are high, this model can no longer be used. Thus, it is recommended that a similar model which considers losses be developed. It is also desirable to test the present DPTL model using nonlinear sources and loads. Once the models for the lossy lines are developed, coupling and cross-talk can be considered next for modeling in terms of lumped circuit components.

APPENDIX A

The Cauer Network

The synthesis considered here is that for the one-port network. Here, Cauer's method (3) is used. Cauer networks are derived from the expansion of a rational fraction (equation (A-1)) into the Stieljes' continued fraction expansion (equation (A-2)) which is the same as equation (11).

$$R(s) = \frac{N(s)}{D(s)} = \frac{A_0 s^m + A_1 s^{m-1} + A_2 s^{m-2} + \dots}{B_0 s^n + B_1 s^{n-1} + B_2 s^{n-2} + \dots} \quad (A-1)$$

Stieljes' continued fraction expansion of (A-1) is

$$R(s) = C_0 s^{m-n} + \frac{1}{C_1 s^{m-n} + \frac{1}{C_2 s^{m-n} + \frac{1}{C_3 s^{m-n} + \frac{1}{\dots}}}} \quad (A-2)$$

$R(s)$ has been used to denote either a driving-point impedance, $Z(s)$, or a driving-point admittance, $Y(s)$.

Depending on the values of the A's and B's, some of the capacitances and inductances may have negative values; this should not disturb anyone since the network is not to be realized. Note that if the network is not to be necessarily realizable, we may consider two possible relationships between m and n of equation (A-1).

$$\begin{array}{l}
 m = n + 1 \left\{ \begin{array}{l}
 R(s) = Z(s) : C_0 s, C_2 s, C_4 s, \dots = \text{inductive reactances} \\
 : C_1 s, C_3 s, C_5 s, \dots = \text{capacitive reactances} \\
 \\
 R(s) = Y(s) : C_0 s, C_2 s, C_4 s, \dots = \text{capacitive reactances} \\
 : C_1 s, C_3 s, C_5 s, \dots = \text{inductive reactances}
 \end{array} \right. \\
 \\
 m = n - 1 \left\{ \begin{array}{l}
 R(s) = Z(s) : C_0/s, C_2/s, C_4/s, \dots = \text{capacitive reactances} \\
 : C_1/s, C_3/s, C_5/s, \dots = \text{inductive reactances} \\
 \\
 R(s) = Y(s) : C_0/s, C_2/s, C_4/s, \dots = \text{inductive reactances} \\
 : C_1/s, C_3/s, C_5/s, \dots = \text{capacitive reactances}
 \end{array} \right. \quad (A-3)
 \end{array}$$

For equation (10), $m = n + 1$ is used:

$$Z(s) = \frac{A_0 s + A_1 s^2 + A_2 s^3 + \dots + A_{10} s^{11}}{B_0 + B_1 s + B_2 s^2 + \dots + B_{10} s^{10}}$$

which yields the network shown in Figure 4.

PROGRAM LISTING

APPENDIX B

LIST TLINE

```
10 COMPLEX Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8,Z9,Z10,Z11,ZINS,TQ,P
20 COMPLEX ZZ1,ZZ2,UU,DN1,DN2,DN3,DN4,DN5,DN,VOD,ZS,ZL,ZO
25 COMPLEX ZINP,UN,DEN1,DEN2,DEN3,DEN4,DEN5,DEN,VOL,T9
30 REAL F,PI,n,LENG,EP,C,F0,F1,F2,LOL
35 REAL Q,QT,T1,T2,T3,T4,T5,T6,FA,SUM
40 REAL BL,BL2,T7,T8,MVOL,MVOD
70 ZO=CMPLX(50.,0.)
72 ZS=CMPLX(10.,-25.)
74 ZL=CMPLX(200.,500.)
80 PI=3.14159265
90 LENG=1.
110 EP=1.
112 WRITE(6,77)LENG,EP
114 77 FORMAT("LENGHT= ",F12.5,3X,"EPSILN= ",F12.5)
116 WRITE(6,76)ZO
117 WRITE(6,75)ZS,ZL
118 76 FORMAT("ZO= ",2E12.5)
119 75 FORMAT("ZS= ",2E12.5,3X,"ZL= ",2E12.5)
120 C=3.E8
122 DO 100 N=10,10000,50
124 F=(FLNAT(N))*1.E6
126 n=2.*PI*n
130 LOL=LENG*n*SQRT(EP)/(3.E8)
140 F0=PI*LOL/n
150 F1=ZO*n*F0
160 F2=F0/ZO
170 T=n*n*F1*.09174664
180 Z1=CMPLX(0.,T)
190 T=-1./(n*n*2*.5417253)
200 Z2=CMPLX(0.,T)
210 T=n*n*F1*(-.0351131)
220 Z3=CMPLX(0.,T)
230 T=1./(n*n*2*.4033141)
240 Z4=CMPLX(0.,T)
250 T=n*n*F1*(.07935403)
260 Z5=CMPLX(0.,T)
270 T=-1./(n*n*2*.2536081)
280 Z6=CMPLX(0.,T)
290 T=n*n*F1*.7765694
300 Z7=CMPLX(0.,T)
310 T=1./(n*n*2*.05267584)
320 Z8=CMPLX(0.,T)
330 T=-1.*n*n*F1*.2371407
340 Z9=CMPLX(0.,T)
350 T=-1./(n*n*2*.5359052)
```

```

360 Z10=CMPLX(0.,T)
370 T=PI*.32458
380 Z11=CMPLX(0.,T)
390 P=Z9+Z10*Z11/(Z10+Z11)
400 P=Z7+Z8*P/(Z8+P)
410 P=Z5+Z6*P/(Z6+P)
420 P=Z3+Z4*P/(Z4+P)
430 ZINS=Z1+Z2*P/(Z2+P)
440 Q=PI*LOL
450 QT=Z0*TAN(Q)
460 TQ=CMPLX(0.,QT)
470 T1=4.*EP*LOL*LOL
480 T2=(4./PI)*LOL*SQRT(EP)
485 T3=1./(2.*PI*LOL*SQRT(EP))
487 SUM=0.
488 FA=-1.
490 GO 99 I=1,20
500 T5=(FLOAT(I))**2-T1
505 T6=FA/T5
510 SUM=T6+SUM
515 FA=-1.*FA
520 99 CONTINUE
522 SUM=T3-T2*SUM
525 SUM=-1.*Z0*SUM
530 ZINP=CMPLX(0.,SUM)
535 UN=ZL*ZINP
540 DEN1=ZS+ZL
545 DEN2=ZINS+ZINP
550 DEN3=ZS*ZL
555 DEN4=ZINS*ZINP*CMPLX(2.,0.)
560 DEN5=ZINS*ZINP
565 DEN=DEN1+DEN2+DEN3+DEN4+DEN5
568 VOL=UN/DEN
569 MVOL=CABS(VOL)
585 BL=LOL*PI*2.
590 BL2=BL/2.
600 T7=TAN(BL2)
605 T8=-1./SIN(BL)
608 T9=CMPLX(0.,T8)
610 ZZ2=T9*Z0
615 ZZ1=Z0*CMPLX(0.,T7)
620 UU=ZL*ZZ2
625 UN1=ZS+ZL
630 DN2=ZZ1+ZZ2
635 UN3=ZS*ZL
640 DN4=ZZ1*ZZ2*CMPLX(2.,0.)

```

```

645 DN5=ZZ1*ZZ2
650 DN=DN1+DN2+DN3+DN4+DN5
655 VOD=UU/DN
657 MVOD=CABS(VOD)
800 WRITE(6,1)F,LOL
830 WRITE(6,2)VOL,VOD
835 WRITE(6,3)MVOL,MVOD
840 1 FORMAT("FREQ.= ",E12.5,3X,"LEN/LAM= ",E12.5)
850 2 FORMAT("VOL= ",2E12.5,3X,"VOD= ",2E12.5)
855 3 FORMAT("MVOL= ",E12.5,3X,"MVOD= ",E12.5)
858 WRITE(6,4)
859 4 FORMAT("-----")
860 100 CONTINUE
870 STOP
880 END

```

Output Samples

RUN TLINE

LENGHT= 1.00000 EPSILON= 1.00000
ZO= 0.50000E 02 0.
ZS= 0.10000E 01 0. ZL= 0.10000E 01 0.
FREQ.= 0.10000E 03 LEN/LAM= 0.33333E-01
VOL= 0.77473E-02-0.62452E-01 VOD= 0.77473E-02-0.62451E-01
MVOL= 0.62930E-01 MVOD= 0.62930E-01
=====

FREQ.= 0.60000E 03 LEN/LAM= 0.20000E 00
VOL= 0.51984E-04-0.91740E-02 VOD= 0.52017E-04-0.91740E-02
MVOL= 0.91742E-02 MVOD= 0.91741E-02
=====

FREQ.= 0.11000E 09 LEN/LAM= 0.36667E 00
VOL= -0.11801E-04-0.29680E-02 VOD= -0.11789E-04-0.29680E-02
MVOL= 0.29680E-02 MVOD= 0.29680E-02
=====

FREQ.= 0.16000E 09 LEN/LAM= 0.53333E 00
VOL= -0.96015E-06 0.70077E-03 VOD= -0.96048E-06 0.70069E-03
MVOL= 0.70077E-03 MVOD= 0.70069E-03
=====

FREQ.= 0.21000E 09 LEN/LAM= 0.70000E 00
VOL= -0.14432E-04 0.48435E-02 VOD= -0.14497E-04 0.48431E-02
MVOL= 0.48435E-02 MVOD= 0.48431E-02
=====

FREQ.= 0.26000E 09 LEN/LAM= 0.36667E 00
VOL= 0.30019E-03 0.14969E-01 VOD= 0.29980E-03 0.14964E-01
MVOL= 0.14972E-01 MVOD= 0.14967E-01
=====

FREQ.= 0.31000E 09 LEN/LAM= 0.10333E 01
VOL= 0.77040E-02-0.62281E-01 VOD= 0.77473E-02-0.62451E-01
MVOL= 0.62756E-01 MVOD= 0.62930E-01
=====

FREQ.= 0.36000E 09 LEN/LAM= 0.12000E 01
VOL= 0.53130E-04-0.92286E-02 VOD= 0.52017E-04-0.91740E-02
MVOL= 0.92288E-02 MVOD= 0.91741E-02
=====

FREQ.= 0.41000E 09 LEN/LAM= 0.13667E 01
VOL= -0.11128E-04-0.32494E-02 VOD= -0.11789E-04-0.29680E-02
MVOL= 0.32494E-02 MVOD= 0.29680E-02
=====

FREQ.= 0.46000E 09 LEN/LAM= 0.15333E 01
VOL= 0.22767E-05-0.57938E-03 VOD= -0.96048E-06 0.70069E-03
MVOL= 0.57938E-03 MVOD= 0.70069E-03
=====

RUN TLINE

```

LENGHT=      1.00000      EPSILN=      1.00000
ZO= 0.50000E 02 0.
ZS= 0.10000E 01 0.
ZI= 0.50000E 02 0.
=====
FREQ.= 0.10000E 08      LEN/LAM= 0.33333E-01
VOL= 0.90909E 00-0.29109E 00      VOD= 0.90909E 00-0.29109E 00
MVOL= 0.95455E 00      MVOD= 0.95455E 00
=====
FREQ.= 0.60000E 08      LEN/LAM= 0.20000E 00
VOL= 0.63851E-01-0.44568E 00      VOD= 0.63890E-01-0.44567E 00
MVOL= 0.45023E 00      MVOD= 0.45022E 00
=====
FREQ.= 0.11000E 09      LEN/LAM= 0.36667E 00
VOL= -0.14830E-01-0.14658E 00      VOD= -0.14815E-01-0.14659E 00
MVOL= 0.14733E 00      MVOD= 0.14733E 00
=====
FREQ.= 0.16000E 09      LEN/LAM= 0.53333E 00
VOL= -0.12224E-02 0.34991E-01      VOD= -0.12223E-02 0.34987E-01
MVOL= 0.35012E-01      MVOD= 0.35008E-01
=====
FREQ.= 0.21000E 09      LEN/LAM= 0.70000E 00
VOL= -0.18133E-01 0.23972E 00      VOD= -0.18213E-01 0.23969E 00
MVOL= 0.24040E 00      MVOD= 0.24038E 00
=====
FREQ.= 0.26000E 09      LEN/LAM= 0.86667E 00
VOL= 0.29834E 00 0.58977E 00      VOD= 0.29807E 00 0.58981E 00
MVOL= 0.66094E 00      MVOD= 0.66085E 00
=====
FREQ.= 0.31000E 09      LEN/LAM= 0.1033E 01
VOL= 0.90867E 00-0.29179E 00      VOD= 0.90909E 00-0.29109E 00
MVOL= 0.95437E 00      MVOD= 0.95455E 00
=====
FREQ.= 0.36000E 09      LEN/LAM= 0.12000E 01
VOL= 0.55209E-01-0.44801E 00      VOD= 0.53890E-01-0.44567E 00
MVOL= 0.45273E 00      MVOD= 0.45022E 00
=====
FREQ.= 0.41000E 09      LEN/LAM= 0.13667E 01
VOL= -0.14016E-01-0.16087E 00      VOD= -0.14815E-01-0.14659E 00
MVOL= 0.16148E 00      MVOD= 0.14733E 00
=====
FREQ.= 0.46000E 09      LEN/LAM= 0.15333E 01
VOL= 0.28747E-02-0.28685E-01      VOD= -0.12223E-02 0.34987E-01
MVOL= 0.28828E-01      MVOD= 0.35008E-01
=====

```

RUN TLINE

LENGHT= 1.00000 EPSILON= 1.00000
 ZO= 0.50000E 02 0.
 ZS= 0.10000E 01 0. ZL= 0.10000E 04 0.

FREQ.= 0.10000E 08 LEN/LAM= 0.33333E-01
 VOL= 0.10209E 01-0.20774E-01 VOD= 0.10209E 01-0.20774E-01
 MVOL= 0.10211E 01 MVOD= 0.10211E 01

FREQ.= 0.60000E 05 LEN/LAM= 0.20000E 00
 VOL= 0.27614E 01-0.11435E 01 VOD= 0.27602E 01-0.11422E 01
 MVOL= 0.29888E 01 MVOD= 0.29872E 01

FREQ.= 0.11000E 09 LEN/LAM= 0.36667E 00
 VOL= -0.11695E 01-0.61359E 00 VOD= -0.11702E 01-0.61456E 00
 MVOL= 0.13207E 01 MVOD= 0.13218E 01

FREQ.= 0.16000E 09 LEN/LAM= 0.53333E 00
 VOL= -0.32556E 00 0.47613E 00 VOD= -0.32553E 00 0.47594E 00
 MVOL= 0.57679E 00 MVOD= 0.57664E 00

FREQ.= 0.21000E 09 LEN/LAM= 0.70000E 00
 VOL= -0.21143E 01 0.15480E 01 VOD= -0.21111E 01 0.15389E 01
 MVOL= 0.26204E 01 MVOD= 0.26124E 01

FREQ.= 0.26000E 09 LEN/LAM= 0.86667E 00
 VOL= 0.14702E 01 0.17902E 00 VOD= 0.14711E 01 0.17973E 00
 MVOL= 0.14811E 01 MVOD= 0.14820E 01

FREQ.= 0.31000E 09 LEN/LAM= 0.10333E 01
 VOL= 0.10210E 01-0.20824E-01 VOD= 0.10209E 01-0.20774E-01
 MVOL= 0.10212E 01 MVOD= 0.10211E 01

FREQ.= 0.36000E 09 LEN/LAM= 0.12000E 01
 VOL= 0.27456E 01-0.11203E 01 VOD= 0.27602E 01-0.11422E 01
 MVOL= 0.29655E 01 MVOD= 0.29872E 01

FREQ.= 0.41000E 09 LEN/LAM= 0.13667E 01
 VOL= -0.13797E 01-0.64376E 00 VOD= -0.11702E 01-0.61456E 00
 MVOL= 0.16172E 01 MVOD= 0.13218E 01

FREQ.= 0.46000E 09 LEN/LAM= 0.15333E 01
 VOL= 0.23431E 00-0.11885E 00 VOD= -0.32553E 00 0.47594E 00
 MVOL= 0.26273E 00 MVOD= 0.57664E 00

RUN TLINE

```

LENGHT=      1.00000      EPSILON=      1.00000
ZO= 0.50000E 02 0.
ZS= 0.50000E 02 0.
ZL= 0.10000E 01 0.
=====
FREQ.= 0.10000E 03      LEN/LAM= 0.33333E-01
VOL= 0.18182E-01-0.58218E-02      VOD= 0.18182E-01-0.58219E-02
MVOL= 0.19091E-01      MVOD= 0.19091E-01
=====
FREQ.= 0.60000E 08      LEN/LAM= 0.20000E 00
VOL= 0.12770E-02-0.89135E-02      VOD= 0.12776E-02-0.89133E-02
MVOL= 0.90046E-02      MVOD= 0.90044E-02
=====
FREQ.= 0.11000E 09      LEN/LAM= 0.36667E 00
VOL= -0.29460E-03-0.29316E-02      VOD= -0.29630E-03-0.29317E-02
MVOL= 0.29466E-02      MVOD= 0.29466E-02
=====
FREQ.= 0.16000E 09      LEN/LAM= 0.53333E 00
VOL= -0.24447E-04 0.69981E-03      VOD= -0.24455E-04 0.69974E-03
MVOL= 0.70024E-03      MVOD= 0.70017E-03
=====
FREQ.= 0.21000E 09      LEN/LAM= 0.70000E 00
VOL= -0.36265E-03 0.47943E-02      VOD= -0.36425E-03 0.47937E-02
MVOL= 0.46080E-02      MVOD= 0.46075E-02
=====
FREQ.= 0.26000E 09      LEN/LAM= 0.86667E 00
VOL= 0.59669E-02 0.11795E-01      VOD= 0.59613E-02 0.11796E-01
MVOL= 0.13219E-01      MVOD= 0.13217E-01
=====
FREQ.= 0.31000E 09      LEN/LAM= 0.10333E 01
VOL= 0.18173E-01-0.58358E-02      VOD= 0.18182E-01-0.58219E-02
MVOL= 0.19087E-01      MVOD= 0.19091E-01
=====
FREQ.= 0.36000E 09      LEN/LAM= 0.12000E 01
VOL= 0.13042E-02-0.89603E-02      VOD= 0.12776E-02-0.89133E-02
MVOL= 0.90547E-02      MVOD= 0.90044E-02
=====
FREQ.= 0.41000E 09      LEN/LAM= 0.13667E 01
VOL= -0.29031E-03-0.32173E-02      VOD= -0.29630E-03-0.29317E-02
MVOL= 0.32295E-02      MVOD= 0.29466E-02
=====
FREQ.= 0.46000E 09      LEN/LAM= 0.15333E 01
VOL= 0.57493E-04-0.57369E-03      VOD= -0.24455E-04 0.69974E-03
MVOL= 0.57657E-03      MVOD= 0.70017E-03
=====

```

RUN TLINE

```

LENGHT= 1.00000 EPSILON= 1.00000
ZO= 0.50000E 02 0.
ZS= 0.50000E 02 0.
ZL= 0.50000E 02 0.
=====
FREQ.= 0.10000E 08 LEN/LAM= 0.33333E-01
VOL= 0.47705E 00-0.12759E 00 VOD= 0.47705E 00-0.12759E 00
MVOL= 0.49381E 00 MVOD= 0.49381E 00
=====
FREQ.= 0.50000E 08 LEN/LAM= 0.20000E 00
VOL= 0.60646E-01-0.30743E 00 VOD= 0.60692E-01-0.30744E 00
MVOL= 0.31335E 00 MVOD= 0.31337E 00
=====
FREQ.= 0.11000E 09 LEN/LAM= 0.36667E 00
VOL= -0.23190E-01-0.12951E 00 VOD= -0.23169E-01-0.12952E 00
MVOL= 0.13157E 00 MVOD= 0.13158E 00
=====
FREQ.= 0.16000E 09 LEN/LAM= 0.53333E 00
VOL= -0.23549E-02 0.34625E-01 VOD= -0.23557E-02 0.34621E-01
MVOL= 0.34705E-01 MVOD= 0.34701E-01
=====
FREQ.= 0.21000E 09 LEN/LAM= 0.70000E 00
VOL= -0.23504E-01 0.19404E 00 VOD= -0.23596E-01 0.19397E 00
MVOL= 0.19546E 00 MVOD= 0.19540E 00
=====
FREQ.= 0.26000E 09 LEN/LAM= 0.86467E 00
VOL= 0.21917E 00 0.34005E 00 VOD= 0.21894E 00 0.34010E 00
MVOL= 0.40456E 00 MVOD= 0.40447E 00
=====
FREQ.= 0.31000E 09 LEN/LAM= 0.10333E 01
VOL= 0.47696E 00-0.12781E 00 VOD= 0.47705E 00-0.12759E 00
MVOL= 0.49379E 00 MVOD= 0.49381E 00
=====
FREQ.= 0.36000E 09 LEN/LAM= 0.12000E 01
VOL= 0.61641E-01-0.30824E 00 VOD= 0.60692E-01-0.30744E 00
MVOL= 0.31435E 00 MVOD= 0.31337E 00
=====
FREQ.= 0.41000E 09 LEN/LAM= 0.13467E 01
VOL= -0.21639E-01-0.14164E 00 VOD= -0.23169E-01-0.12952E 00
MVOL= 0.14329E 00 MVOD= 0.13158E 00
=====
FREQ.= 0.46000E 09 LEN/LAM= 0.15333E 01
VOL= 0.55443E-02-0.25049E-01 VOD= -0.23557E-02 0.34621E-01
MVOL= 0.28591E-01 MVOD= 0.34701E-01
=====

```

RUN TLINE

```

LENGHT=      1.00000      EPSILON=      1.00000
ZO= 0.50000E 02 0.
ZS= 0.50000E 02 0.
FREQ.= 0.10000E 08      LEN/LAM= 0.33333E-01
VOL= 0.92957E 00-0.20245E 00      VOD= 0.92957E 00-0.20245E 00
MVOL= 0.95136E 00      MVOD= 0.95136E 00
=====
FREQ.= 0.60000E 08      LEN/LAM= 0.20000E 00
VOL= 0.26375E 00-0.86246E 00      VOD= 0.26402E 00-0.86255E 00
MVOL= 0.90189E 00      MVOD= 0.90205E 00
=====
FREQ.= 0.11000E 09      LEN/LAM= 0.36667E 00
VOL= -0.42322E 00-0.65010E 00      VOD= -0.42321E 00-0.65058E 00
MVOL= 0.77572E 00      MVOD= 0.77612E 00
=====
FREQ.= 0.16000E 09      LEN/LAM= 0.53333E 00
VOL= -0.27546E 00 0.43872E 00      VOD= -0.27548E 00 0.43856E 00
MVOL= 0.51802E 00      MVOD= 0.51790E 00
=====
FREQ.= 0.21000E 09      LEN/LAM= 0.70000E 00
VOL= -0.22400E 00 0.80209E 00      VOD= -0.22453E 00 0.80098E 00
MVOL= 0.83279E 00      MVOD= 0.83186E 00
=====
FREQ.= 0.26000E 09      LEN/LAM= 0.86667E 00
VOL= 0.61185E 00 0.70422E 00      VOD= 0.61115E 00 0.70452E 00
MVOL= 0.93289E 00      MVOD= 0.93266E 00
=====
FREQ.= 0.31000E 09      LEN/LAM= 0.10333E 01
VOL= 0.92958E 00-0.20257E 00      VOD= 0.92957E 00-0.20245E 00
MVOL= 0.95140E 00      MVOD= 0.95136E 00
=====
FREQ.= 0.36000E 09      LEN/LAM= 0.12000E 01
VOL= 0.26559E 00-0.36048E 00      VOD= 0.26402E 00-0.86255E 00
MVOL= 0.90053E 00      MVOD= 0.90205E 00
=====
FREQ.= 0.41000E 09      LEN/LAM= 0.13467E 01
VOL= -0.39161E 00-0.74456E 00      VOD= -0.42321E 00-0.65058E 00
MVOL= 0.84127E 00      MVOD= 0.77612E 00
=====
FREQ.= 0.46000E 09      LEN/LAM= 0.15333E 01
VOL= 0.23764E 00-0.10132E 00      VOD= -0.27548E 00 0.43856E 00
MVOL= 0.25834E 00      MVOD= 0.51790E 00
=====

```

RUN TLINE

```

LENGHT=      1.00000      EPSILON=      1.00000
ZO= 0.50000E 02 0.
ZS= 0.10000E 04 0.
FREQ.= 0.10000E 08      LEN/LAM= 0.33333E-01      ZL= 0.10000E 01 0.
VOL= 0.10209E-02-0.20774E-04      VOD= 0.10209E-02-0.20774E-04
MVOL= 0.10211E-02      MVOD= 0.10211E-02
=====
FREQ.= 0.60000E 08      LEN/LAM= 0.20000E 00
VOL= 0.27614E-02-0.11435E-02      VOD= 0.27602E-02-0.11422E-02
MVOL= 0.29888E-02      MVOD= 0.29872E-02
=====
FREQ.= 0.11000E 09      LEN/LAM= 0.36667E 00
VOL= -0.11695E-02-0.61359E-03      VOD= -0.11702E-02-0.61458E-03
MVOL= 0.13207E-02      MVOD= 0.13218E-02
=====
FREQ.= 0.16000E 09      LEN/LAM= 0.53333E 00
VOL= -0.32556E-03 0.47613E-03      VOD= -0.32558E-03 0.47594E-03
MVOL= 0.57679E-03      MVOD= 0.57664E-03
=====
FREQ.= 0.21000E 09      LEN/LAM= 0.70000E 00
VOL= -0.21143E-02 0.15480E-02      VOD= -0.21111E-02 0.15389E-02
MVOL= 0.26204E-02      MVOD= 0.26124E-02
=====
FREQ.= 0.26000E 09      LEN/LAM= 0.36667E 00
VOL= 0.14702E-02 0.17902E-03      VOD= 0.14711E-02 0.17933E-03
MVOL= 0.14811E-02      MVOD= 0.14820E-02
=====
FREQ.= 0.31000E 09      LEN/LAM= 0.10333E 01
VOL= 0.10210E-02-0.20824E-04      VOD= 0.10209E-02-0.20774E-04
MVOL= 0.10212E-02      MVOD= 0.10211E-02
=====
FREQ.= 0.36000E 09      LEN/LAM= 0.12000E 01
VOL= 0.27458E-02-0.11203E-02      VOD= 0.27602E-02-0.11422E-02
MVOL= 0.29655E-02      MVOD= 0.29872E-02
=====
FREQ.= 0.41000E 09      LEN/LAM= 0.13667E 01
VOL= -0.13797E-02-0.84378E-03      VOD= -0.11702E-02-0.61458E-03
MVOL= 0.16172E-02      MVOD= 0.13218E-02
=====
FREQ.= 0.46000E 09      LEN/LAM= 0.15333E 01
VOL= 0.23431E-03-0.11885E-03      VOD= -0.32558E-03 0.47594E-03
MVOL= 0.26273E-03      MVOD= 0.57664E-03
=====

```

RUN TLINE

```

LENGHT=      1.0000      EPSILON=      1.0000
ZO= 0.5000E 02 0.
ZS= 0.1000E 04 0.
FREQ.= 0.1000E 08      LEN/LAM= 0.3333E-01      ZL= 0.5000E 02 0.
VOL= 0.46478E-01-0.10122E-01      VOD= 0.46478E-01-0.10122E-01
MVOL= 0.47568E-01      MVOD= 0.47568E-01
=====
FREQ.= 0.6000E 08      LEN/LAM= 0.2000E 00
VOL= 0.13188E-01-0.43123E-01      VOD= 0.13201E-01-0.43127E-01
MVOL= 0.45094E-01      MVOD= 0.45103E-01
=====
FREQ.= 0.1100E 09      LEN/LAM= 0.3666E 00
VOL= -0.21161E-01-0.32505E-01      VOD= -0.21161E-01-0.32529E-01
MVOL= 0.38786E-01      MVOD= 0.38806E-01
=====
FREQ.= 0.1600E 09      LEN/LAM= 0.5333E 00
VOL= -0.13773E-01 0.21936E-01      VOD= -0.13774E-01 0.21928E-01
MVOL= 0.25901E-01      MVOD= 0.25895E-01
=====
FREQ.= 0.2100E 09      LEN/LAM= 0.7000E 00
VOL= -0.11200E-01 0.40105E-01      VOD= -0.11226E-01 0.40049E-01
MVOL= 0.41639E-01      MVOD= 0.41593E-01
=====
FREQ.= 0.2600E 09      LEN/LAM= 0.8666E 00
VOL= 0.30593E-01 0.35211E-01      VOD= 0.30558E-01 0.35234E-01
MVOL= 0.46645E-01      MVOD= 0.46633E-01
=====
FREQ.= 0.3100E 09      LEN/LAM= 0.1033E 01
VOL= 0.46479E-01-0.10123E-01      VOD= 0.46476E-01-0.10122E-01
MVOL= 0.47570E-01      MVOD= 0.47568E-01
=====
FREQ.= 0.3600E 09      LEN/LAM= 0.1200E 01
VOL= 0.13280E-01-0.43024E-01      VOD= 0.13201E-01-0.43127E-01
MVOL= 0.45027E-01      MVOD= 0.45103E-01
=====
FREQ.= 0.4100E 09      LEN/LAM= 0.1366E 01
VOL= -0.19581E-01-0.37223E-01      VOD= -0.21161E-01-0.32529E-01
MVOL= 0.42063E-01      MVOD= 0.38806E-01
=====
FREQ.= 0.4600E 09      LEN/LAM= 0.1533E 01
VOL= 0.11382E-01-0.50661E-02      VOD= -0.13774E-01 0.21928E-01
MVOL= 0.12917E-01      MVOD= 0.25395E-01
=====

```

RUN TLINE

```

LENGHT=      1.00000   EPSILON=      1.00000
ZO=  0.50000E 02 0.
ZS=  0.10000E 04 0.
ZL=  0.10000E 04 0.
-----
FREQ.= 0.10000E 08   LEN/LAM= 0.33333E-01
VOL=  0.92062E-01-0.19643E 00   VOD=  0.92064E-01-0.19643E 00
MVOL= 0.21693E 00   MVOD=  0.21693E 00
-----
FREQ.= 0.60000E 08   LEN/LAM= 0.20000E 00
VOL=  0.16850E-02-0.52204E-01   VOD=  0.16870E-02-0.52219E-01
MVOL= 0.52231E-01   MVOD=  0.52246E-01
-----
FREQ.= 0.11000E 09   LEN/LAM= 0.36467E 00
VOL= -0.57492E-02-0.65257E-01   VOD= -0.57479E-02-0.65284E-01
MVOL= 0.65510E-01   MVOD=  0.65537E-01
-----
FREQ.= 0.16000E 09   LEN/LAM= 0.53333E 00
VOL= -0.55847E-01 0.15951E 00   VOD= -0.55856E-01 0.15947E 00
MVOL= 0.16901E 00   MVOD=  0.16897E 00
-----
FREQ.= 0.21000E 09   LEN/LAM= 0.70000E 00
VOL= -0.16657E-02 0.52007E-01   VOD= -0.16700E-02 0.51955E-01
MVOL= 0.52034E-01   MVOD=  0.51982E-01
-----
FREQ.= 0.26000E 09   LEN/LAM= 0.84467E 00
VOL=  0.59715E-02 0.66510E-01   VOD=  0.59561E-02 0.66447E-01
MVOL= 0.66778E-01   MVOD=  0.66713E-01
-----
FREQ.= 0.31000E 09   LEN/LAM= 0.10333E 01
VOL=  0.92009E-01-0.19639E 00   VOD=  0.92064E-01-0.19643E 00
MVOL= 0.21688E 00   MVOD=  0.21693E 00
-----
FREQ.= 0.36000E 09   LEN/LAM= 0.12000E 01
VOL=  0.16970E-02-0.52129E-01   VOD=  0.16870E-02-0.52219E-01
MVOL= 0.52157E-01   MVOD=  0.52246E-01
-----
FREQ.= 0.41000E 09   LEN/LAM= 0.13467E 01
VOL= -0.45436E-02-0.65501E-01   VOD= -0.57479E-02-0.65284E-01
MVOL= 0.65658E-01   MVOD=  0.65537E-01
-----
FREQ.= 0.46000E 09   LEN/LAM= 0.15333E 01
VOL=  0.13067E 00 0.46820E-01   VOD= -0.35856E-01 0.15947E 00
MVOL= 0.13880E 00   MVOD=  0.16897E 00
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