Transmission Line Design for a Power Distribution System at 20 kHz for Aircraft

Leon W. Zelby, John B. Mathes, and John W. Shawver

GRANT NAG3-508
JULY 1986
Transmission Line Design for a Power Distribution System at 20 kHz for Aircraft

Leon W. Zelby, John B. Mathes, and John W. Shawver
University of Oklahoma
Norman, Oklahoma

Prepared for
Lewis Research Center
under Grant NAG3-508

NASA
National Aeronautics
and Space Administration
Scientific and Technical
Information Branch
1986
1.0 INTRODUCTION

The purpose of this work is to design a transmission line for a power distribution system in aircraft. The line is to operate at 20 kHz, have very low inductance and, consequently, a low characteristic impedance; it must withstand 440 V at an altitude of 15 km (50,000 ft) and 1 kV at 300 km (about 100,000 ft), and must be capable of carrying 100 A. The connectors and supports must have a minimum creepage path of 0.635 cm (1/4 in.).

Additional considerations of the line design include connectors for parallel loads, number of such connectors, mechanical strength and heat dissipation, dc resistance, and weight.

The fundamental problem in determining the inductance per unit length, and the characteristic impedance of the line is the calculation of inductance or capacitance because \( LCv^2 = 1 \), with \( L \) and \( C \) representing the inductance and capacitance per unit length, respectively; and \( v \) representing the velocity of wave propagation along the line (in the case of the fundamental mode, the TEM mode, the velocity is governed by the properties of the material between the wires). At a frequency of 20 kHz, the skin depth for copper (resistivity 1.7x10^{-8} \, \Omega \cdot \text{m}, conductivity = 5.88x10^7 \, \text{mho/m}) is 0.46 mm at 0.5 mm, and the wavelength in free space, is 15.0 km and about 9.0 km in many commercially used insulating materials (relative dielectric constant on the order of 3). Thus, the total length of the line is on the order of 0.02 to 0.033 wavelength which justifies the quasi-static approximations (refs. 1 to 5). The close spacing among the individual conductors strengthen the validity of the relation \( LCv^2 = 1 \) and of the "quasi-TEM" mode dominance. [Strictly speaking, the TEM mode in this case is not absolutely pure because of two factors: there are two dielectrics between the wires, the insulation and air; and the wires are lossy. As a consequence, there will be an axial component of the electric field, but it is so small that the assumption about TEM is more than satisfactory for practical purposes. Furthermore, with reasonable insulation the shunt conductance (between the wires) will be on order of \( 10^{-17} \, \text{mho/m} \) (ref. 6). As a consequence, the term \( RG/\omega^2LC \) will be on the order of \( 10^{-14} \ll 1 \), so that the propagation constant will very nearly be equal to \( \omega \sqrt{LC} \), so that the relation \( LCv^2 = 1 \) will be satisfied in any practical system.]

The SI system of units will be used throughout this report.

2.0 DETERMINATION OF PARAMETERS

2.1 Introduction

In order to design a suitable transmission line, several parameters need to be determined for different configurations. The parameters are \( L \), the inductance per unit length; \( C \), the capacitance per unit length; \( Z_0 \), the
characteristic impedance; and $R$, the resistance per unit length. ($G$, the shunt conductance per unit length is too small to be included.) $L$ and $C$ are related as indicated above through the relation $LCv^2 = 1$; also, for a lossless line, $Z_0 = (L/C)^{1/2}$. At a frequency of 20 kHz, the skin depth in copper is 0.467 mm, with the current distributed in a circular cylindrical conductor as shown in figure 1. The distribution is governed by the relation (ref. 7)

$$\frac{I_z}{I_0} = \frac{\text{Ber} \left( \frac{r\sqrt{2}}{\delta} \right) + j\text{Bei} \left( \frac{r\sqrt{2}}{\delta} \right)}{\text{Ber} \left( \frac{r_0\sqrt{2}}{\delta} \right) + j\text{Bei} \left( \frac{r_0\sqrt{2}}{\delta} \right)}$$

where $\text{Ber}(x) + j\text{Bei}(x) = J_0(j^{-1/2}x)$, with $J_0(x)$ the Bessel function of the first kind and zeroth order, and $j = (-1)^{1/2}$. The other symbols are: $r$, radial distance; $r_0$, the radius of the wire; and $\delta$, the skin depth. In view of this distribution, calculations will be concerned mainly with wires whose diameter does not exceed 1 mm (number 18 AWG wire).

The main parameter is the inductance which should be as low as possible in order to minimize the effects of switching. Consequently, emphasis will be placed on the determination of $L$ which will be calculated two different ways: one method will utilize the definition of inductance (flux linkage per unit current); the other method will utilize the calculation of capacitance from which the inductance will be evaluated from the relation $L = (Cv^2)^{-1} = \mu\varepsilon/C = Z_0\sqrt{\mu\varepsilon}$.

2.2 Inductance Calculations

In the following calculations, the permeability of all materials will be assumed to be that of free space ($\mu_0 = 4\pi\times10^{-7}$ H/m). The inductance per unit length of a bifilar lead of radius $r_a$ (current in each direction is assumed uniformly distributed over the cross section of the wire, see fig. 1) separated from the return lead of radius $r_{a'}$ by a distance $D_{aa'}$ is (ref. 8)

$$L_{aa'} = \frac{\mu_0}{2\pi} \left[ \frac{1}{2} + \ln \left( \frac{D_{aa'}^2}{r_a r_{a'}} \right) \right] = \frac{\mu_0}{4\pi} \left[ 1 + 4 \ln \left( \frac{D_{aa'}}{r_a} \right) \right] \text{H/m}$$

when the return wire radius is the same as in the first wire (the case here under consideration). For an $n$ wire system ($n$ pairs) one can form an $n \times n$ matrix
where \( L_{ij} = L_{ji} \), and calculate the equivalent inductance of the system (refs. 9 and 10)

\[
L_{eq} = \left( \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{1}{L_{ij}} \right)^{-1} \quad \text{H/m}
\]  

which can be determined to any given degree of accuracy (ref. 10).

The FORTRAN program for this calculation, CRIMPD.F, which is listed in appendix A, uses a series of menus to facilitate the entry of different two-dimensional conductor geometries. The entries are the coordinates of the centers of the conductors and their respective radii, and they may be entered either in rectangular or polar coordinates, (see figs. 2 and 3 for the polar coordinates).

2.3 Check on Calculations

To check the results obtained from calculations performed according to the above discussion, two additional calculations were performed for several geometries. One check used the extension of equation (2) to multiple parallel conductors

\[
L_a = \frac{\mu_0}{2\pi} \left( \frac{1}{2} + 2 \ln \frac{D_{ab} + D_{ac} + \ldots + D_{an}}{r_a \cdot D_{ab} \cdot D_{ac} \cdot \ldots \cdot D_{an}} \right) \quad \text{H/m}
\]  

with the parameters defined in figure 4. The equivalent inductance per unit length was calculated using

\[
L_{eq} = \left( \sum_{i=1}^{n} \frac{1}{L_i} \right)^{-1} + \left( \sum_{i=1}^{n} \frac{1}{L_i} \right)^{-1} \quad \text{H/m}
\]  

3
Calculations for 4-, 8-, and 16-conductor arrangements agreed exactly with the other calculations.

The other check utilized the expression for capacitance between two infinitely long conductors of circular cross section (ref. 11) (radius \( r \), distance between centers \( D \))

\[
C = \frac{\pi \varepsilon}{\cosh^{-1} \left( \frac{D}{2r} \right)} = \frac{\pi \varepsilon}{\ln \left( \frac{D}{2r} + \sqrt{\left( \frac{D}{2r} \right)^2 - 1} \right)} \text{ F/m} \tag{7}
\]

so that the external self-inductance of one conductor is

\[
L = \frac{\mu}{2\pi} \ln \left( \frac{D}{2r} + \sqrt{\left( \frac{D}{2r} \right)^2 + 1} \right) \text{ H/m} \tag{8}
\]

because \( LC = \mu \varepsilon \). Calculations were performed using the above argument of the logarithmic function instead of using the \( D_{ij} \)'s. The results, for the ratio of the distance between conductor centers to conductor radius equal to four, are about 7 percent lower than the other calculations. This was to be expected because the internal inductance, \( \mu / 8\varepsilon \), does not appear in equation (8), but its contribution is negligible for the distance-to-radius ratio of four or more, and the 7 percent discrepancy is well within bounds (ref. 10). Note that the dimensional relations of this report meet this criterion: the ratio of the distance between centers to conductor radius never is less than four. Consequently, the error—if any—should not exceed 7 percent, a value usually acceptable in practice.

3.0 CONFIGURATION DATA

3.1 Circular Cylindrical Arrangements

Calculations were performed for wire arrangements of the type shown in figures 2 and 3. For the single "ring" of wires, as in figure 2, it was found that the best arrangements (i.e., the lowest values of inductance and characteristic impedance) were for alternating current directions in adjacent wires. The values of inductance decrease with increasing number of wires. This circular configuration was not suitable, however, because of the large number of wires needed to reduce the characteristic impedance to acceptable values (on the order of an ohm). Furthermore, with an increasing number of wires, the radius of the "ring" \( R \) is increasing, and this leads to inefficient use of space.

A better configuration was of the multiring variety. Tables I and II list values of \( L \) per unit length, and of \( Z_0 \) for different number of wires (\( N \) represents the total number of wires in the line, with \( N/2 \) in the inner and \( N/2 \) in the outer ring). The angle \( \theta \) is defined in figure 3 and represents the shift of the first wire in the outer ring relative to the first wire in the inner ring. As in the case of the single ring, the lowest values were obtained for alternating polarities.
One of the problems with the coaxial arrangement is that the inductances of the wires in the inner ring are lower so that more current is concentrated there relative to the outer ring. This can be compensated by reducing the radii of the wires in the inner loop.

For comparison of the different wire radii, calculations for the arrangement shown in figure 5 were made. The values for the five ring arrangement for the same wire radii (Line 1), and for different radii (Line 2), are listed in Table III. These show that in the latter case, the overall inductance is increased which means that an increase in the number of wires would be required. Clearly, this again suggests not only an inefficient use of space, but also higher $L$ and $Z_0$ values than comparable rectangular arrangement (see items 1 and 2 of Table IV).

### 3.2 Rectangular Arrangement

To carry 100 A, #4 AWG wire is recommended (ref. 12) whose cross section is $21.15 \times 10^{-6}$ m$^2$. Inasmuch as the skin depth at 20 kHz is approximately 0.5 mm, the largest reasonable wire would be #18 AWG (radius, 0.512 mm; cross-sectional area, 0.8231 mm$^2$). The minimum number of #18 AWG wires would therefore be 26. In subsequent calculations, a larger number of wires will be used. (Note: the 26 wires do not include the return path which calls for additional 26 wires. The minimum for the line would then be 52 wires #18 AWG.)

Figures 6 to 8 show the results of 80-wire 4 by 20 rectangular arrangement which appears to have the best parameters: $L = 10.4$ nH/m; $C = 2.5$ nF/m; $Z_0 = 2.1$ Ω (the computer printed values were, respectively, 10.4196, 2.5264, 2.0611). As the method to compute these values was the "inductance" method, the numbers represent the upper bound. The wires in calculation were #18 AWG, total cross-sectional area in one direction is 32.68 mm$^2$.

A calculation for 256 wires #24 AWG in an 8 by 32 arrangement, as shown in figure 9, was also made. As expected, the inductance and characteristic impedance values are lower than for the 80-wire configuration: $L = 3.2$ nH/m, $C = 7.9$ nF/m, $Z_0 = 0.6$ Ω (printout values, respectively, 3.2193, 7.9382, 0.6368); cross-sectional area, 25.1 mm$^2$. Note that the variations of the self-inductance of the individual wires are greater than for the 80-wire arrangement.

Given the same size wires and the same distances among them, inductances of different size bundles are proportional to the inverse ratio of the number of conductors in the bundle. This was used to arrive at the values listed in Table V for the minimum number of wires required to pass 100-A currents. (If the self-inductances of each of the wires were the same, this relation would hold for any number of wires. Inasmuch as this is not the case (see figs. 7 to 9), the number of wires should be greater than about 20 for the approximation to be acceptable.)

Table V lists several parameters for lines composed of a minimum number of conductors that can carry the rated (100-A) current. The line lengths are 150 m each, so that the dc resistances were calculated for 300-m length to take into account the return path. The total number of wires in each line is twice that listed in the table. The corrections for the ac values were taken from
standard tables (ref. 13), and those for proximity effects from Smith (ref. 14). The proximity effects account for about additional 40 percent of resistance (see Table I and fig. 5 of ref. 14) for a distance-to-radius ratio of four (two in ref. 14 because the distance between the centers in this reference is "2c").

To adjust the value of inductance per unit length and characteristic impedance of the 52-wire #18 AWG line listed in Table V, it is only necessary to multiply by \( \frac{80}{52} = 1.5 \), which would make \( 9.7 < L < 16 \text{ nH/m} \), and \( 1.9 < Z_0 < 3.2 \text{ \Omega} \). Similar adjustments can be made for the other lines.

### 3.3 Miscellaneous Considerations

At the rated current, about 6.5 W will be dissipated per meter of line, which would mean an increase (ref. 15) between 0.08 to 0.13 K, depending upon the type of insulation. Such temperature rise is not sufficiently large to cause concern.

The coefficient of expansion for copper is on the order of \( 10^{-6} \text{ m/K} \) from 25 to 1200 K (ref. 16). At 300 K, the expansion is \( 16.8 \times 10^{-6} \text{ m} \), which would mean a total of 2.5 mm for the entire 150-m line. This, too, is not considered significant.

For the recommended types of aircraft wire (ref. 17), Mil-W-16878, the dielectric strengths substantially exceed the specification of standing off 1 kV, which - for the recommended configuration - would be on the order 1 kV/mm = 1 MV/m = 25 V/mil. The breakdown strength of polyethylene exceeds 20 kV/mm at 20 kHz, as does that of polystyrene, Teflon, and polypropylene (ref. 18).

The conductance per unit length between the individual conductors can be calculated from the relation

\[
\frac{C}{G} = \frac{\varepsilon}{\sigma} \quad (9)
\]

which, for the materials under consideration, will be on the order of \( 10^{-15} \text{ mho/m} \) (\( R \) of the order of \( 10^{15} \text{ \Omega/m} \)), using \( 10^{17} \text{ \Omega-m} \) for resistivity (ref. 6). Clearly the losses due to transverse currents can be neglected.

### 3.4 Connectors and Junction Boxes

A conventional, circular, multipin connector is shown in figure 10 as an example. Junction boxes with connecting wires, with conventional connectors of circular or rectangular shape will fulfill the specifications. The junction box shown in figures 11(a) and (b) would be more suitable, however, because the interconnecting plates substituted for wires would reduce the inductance locally. Connectors could be of the conventional, multipin variety, with soldered or brazed connections internally. Alternatively, internally the pins could be connected to blades for contact with the conductors. The specific configuration is not very critical, but it would be recommended that the connecting surfaces be gold-plated. The reason for this is to prevent increases of contact resistances as a result of fretting (ref. 19).
3.5 Miscellaneous

In addition to the configurations described above, parallel-plate arrangements of the type shown in figures 12 and 13 were analyzed. That of figure 12, in spite of the very low characteristic impedance (0.14 \( \Omega \)), is thought to be less suitable than the configurations recommended in the next section of the report because the thin plates will very likely buckle. Should the plates be made thicker, the line would be too heavy and too unwieldy. Also, connectors with suitable characteristics would be difficult to design.

The program for the determination of line parameters for the configuration shown in figure 13, for different values of \( \theta \), thickness, and spacing, is listed in appendix B. The values of inductances per unit length, and characteristic impedances are at least four times larger than those of the configuration shown in figure 6.

4.0 RECOMMENDATIONS

The line recommendations are made on the basis of the assumption that off-the-shelf availability, or ease for assembly-line production, are secondary to the other attributes such as low impedance, reliability, and the like. As a result, the best choices for the line are listed in Table IV. The total number of wires per 150-m line is listed, with one-half representing the return path. The direction of current alternates between neighboring lines. (The difference between Table IV and Table V is that in the latter one-half of the wires was used in a 300-m long loop for the determination of the total resistance, whereas the number of wires in the former represent two parallel sets each 150 m long.) The alternating current directions have at least two advantages: lowering the inductance of the comparable wire arrangement with adjacent currents in the same direction by at least a factor of four, and by reducing the external magnetic fields which reduces electromagnetic interference. Numbers 1 and 6 in Table IV represent the configurations of figures 6 and 9; the remainder represents the minimum number of wires required for 100-A currents.

Multipin connectors of the type generally available from manufacturers such as Litton, Amphenol, or others, would be satisfactory for the junction boxes shown in figure 11, with gold-plated contacts to prevent increases of resistance due to fretting (platinum plating would also be acceptable).

A general recommendation for any type of line used in an aircraft power distribution system is that instead of one line 150 m long there should be several 5-, 10-, or 15-m sections connected in series via junction boxes. The advantage of this would be that in case of failure of a section, it could be easily replaced—even in flight. Also, the several junction boxes at given intervals would facilitate connections to the respective loads.
PROGRAM CRIMPD

! DOUBLE PRECISION A, C
! DOUBLE PRECISION S(I:1024), O(I:1024), X(I:1024), Y(I:1024)
! DOUBLE PRECISION D(I:1024), T(I:1024), R(I:1024), B(I:1024)
! DOUBLE PRECISION SA, SD, PI, SLOPEANG
! INTEGER MAXU, UU, JJ, ALTPOL
! INTEGER U, J, I, RP(I:1024)

PARAMETER (PI=3.141592654)

Q1="SELECTION IS OUT OF BOUNDS. TRY AGAIN..."

CONTINUE DO 140 I=1,64
PRINT* S(I)=O. G(I)=X. X(I)=Y. L(I)=L1(I)=0. T(J)=R(J)=B(I)=U.
CONTINUE N=1
PRINT"(({"I)"'
PRINT"," 1. PRINT*,' 2. PRINT*,' 3. PRINT*,' 4. PRINT*,' 5. PRINT",'
6. PRINT*,'
7. PRINT*,'
8. PRINT'Cln'
PRINT*,'Choose from REAO*,U IF(U .EQ. H(U .EQ. IF(U .EQ. IFCU .EQ. IFW .EO. IFCU .EO. Q1 
7) GOTO 6)GOTO 5)60TO 4)GOTO 3)GOTO 2)GOTO 1) GOTO 8)
200 PRINT*,'ROUTINE NOT GOTO 200 OPERATIVE, CHOOSE ANOTHER MODE ••• •
250 PRINT*,'AUTO POLAR RING' PRINT*,'Input number of conductors in this ring...'
READ*,U IF(U .EQ. 2)GOTO 200 IF(U .EQ. 1)GOTO 1000
PRINT*,'AUTO POLAR RING' PRINT*,'Input number of conductors in this ring...'
READ*,U SA=2.0*PI/REAL(M)
SD=SA*180.0/PI
PRINT*, 'Input coordinates, radius and polarity of 1st conductor'
PRINT*, 'in this ring (r(mm),theta(degrees),radius(mm),+ or -)'
READ(S,1110) S(N),H,N),R(N),POL(N)
1110 FORMAT(F8.4,F8.4,F8.4,A1)
O(N)=T(N)*PI/180.0
S(N)=S(N)/1000.0
H(N)=H(N)/1000.0
X(N)=S(N)*COS(O(N))
Y(N)=S(N)*SIN(O(N))
MP(N)=0
1120 PRINT*/'(/A)', 'Choose polarity of wires...'
PRINT*/ 1. Alternating
PRINT*/ 2. All the same as 1st
PRINT*/ 3. Individually selected
PRINT*/ 4. Exit to last menu
READ*,U
IFU.EQ.1 GOTO 1200
IFU.EQ.2 GOTO 1180
IFU.EQ.3 GOTO 1160
IFU.EQ.4 GOTO 1000
PRINT*,Q1
GOTO 1120
UUU=1
GOTO 1260
UUU=0
GOTO 1260
1220 UU1=1
GOTO 1260
1260 I=N+1,N+M-1
RPU)=O
SCI)=S(N)
O(I)=O(I-1)+SA
Y(I)=S(I)*COS(O(I))
Y(I)=S(I)*SIN(O(I))
1280 IFUUU NE 1 GOTO 1300
PRINT*,'Conductor, 1 with coords. (r(mm),theta(degrees),radius(mm),polarity(+ or -)'
READ*,A,POL(I)
IF(POL(I).EQ.1)POL(I)='-'
IF(POL(I).EQ.-1)POL(I)=''
CONTINUE
N=N+1
GOTO 1500
1500 H=N*K
GOTO 200
* *
* Individual polar input
* 1500 PRINT* 'Individual Polar Inputs'
PRINT* 'How many conductors in this series?'
READ*,K
DO 1560 I=N,N+K-1
PRINT*,'Conductor, I with coords. (r(mm),theta(degrees),radius(mm),polarity(+ or -)'
READ(S,1110) S(I),H(I),R(I),POL(I)
1560 CONTINUE
N=N+K
GOTO 200
* *
* Rectangular coordinate input
* 2000 PRINT* 'RECTANGULAR COORDINATE INPUT'
PRINT*/ 'Choose one...'
PRINT*/ 1. Individual input
PRINT*/ 2. Line input (equally spaced wires)
PRINT*/ 3. Return to main menu
READ*,U
IFU.EQ.1 GOTO 2120
IFU.EQ.2 GOTO 2200
IFU.EQ.3 GOTO 200
2120 PRINT*, 'Individual Rectangular Inputs'
2130 READ=K
2140 DO 2150 I=N,N+K-1
2150 PRINT*, 'Input coordinates, radius & polarity of cond. I-',
PRINT*, 'CX(mm), Y(mm), rCmm), + or -)
READ*(1110) X(I), Y(I), R(I), POL(I)
RP(I)=1
IF (X(I) .EQ. 0.0) GOTO 2140
\( Y(I)/1000.0
IF (Y(I) .EQ. 0.0) GOTO 2150
\( R(I)/1000.0
\( \text{S(I)=SQRT(X(I)**2.0+Y(I)**2.0)
IF (S(I) .EQ. 0.0) GOTO 2140
\( T(I)=180.0/PI*ACOS(X(I)/S(I))
GOTO 2150
IF (T(I) .EQ. 0.0) GOTO 2150
\( N=N+K
GOTO 200
*
* AUTO LINE
2200 CONTINUE
PRINT*, 'AUTO LINE INPUT'
PRINT*, 'Input coordinates, radius & polarity of 1st conductor...
PRINT*, 'CX(mm), Y(mm), rCmm), + or -)
READ*(1110) X(1), Y(1), R(1), POL(1)
\( X(1)=X(1)/1000.0
\( Y(1)=Y(1)/1000.0
\( R(1)=R(1)/1000.0
\( \text{S(1)=SQRT(X(1)**2.0+Y(1)**2.0)
IF (S(1) .EQ. 0.0) GOTO 2210
\( T(1)=180.0/PI*ACOS(X(1)/S(1))
GOTO 2230
\( T(1)=0.0
\( N=1
CONTINUE
PRINT*, 'Input number of conductors on this line...
READ=K
\( X(N)=X(N)/1000.0
\( Y(N)=Y(N)/1000.0
\( R(N)=R(N)/1000.0
\( \text{S(N)=SQRT(X(N)**2.0+Y(N)**2.0)
IF (S(N) .EQ. 0.0) GOTO 2210
\( T(N)=180.0/PI*ACOS(X(N)/S(N))
GOTO 2230
\( T(N)=0.0
\( N=N+1
CONTINUE
PRINT*, 'Input distance between centers of cond. on this line (SPACING)...
READ=SPACING<br>SPACING=SPACING/1000.0
PRINT*, 'Input slope angle of the line (positive k-axis=0 degrees)
READ=SLOPEANG
SLOPEANG=SLOPEANG*PI/180.0
2300 CONTINUE
DO 2300 I=N+1,N+M-1
\( X(I)=X(I-1)+\text{SPACING*COS(SLOPEANG)}
\( Y(I)=Y(I-1)+\text{SPACING*SIN(SLOPEANG)}
\( R(I)=R(I-1)
\( \text{S(I)=SQRT(X(I)**2+Y(I)**2)
\( T(I)=ACOS(X(I)/S(I))*180.0/PI
\( RP(I)=1
\)
GOTO 2300
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
\)
CONTINUE  
N=N+M  
GOTO 200

CONTINUE  
DO 2400 I=N+1,N+M-1  
P(I)=POL(N)  
CONTINUE  
N=N+M  
GOTO 200

CONTINUE  
DO 2420 I=N+1,N+M-1  
PRINT"(f12.A13/A1.f8.5,2X,F8.4)"  
"conductor"I,"with coords. x(mm)=",X(I),",y(mm)=",Y(I)  
PRINT"++Input polarity (+ or -)++"  
CONTINUE  
N=N+M  
GOTO 200

CONTINUE  
N=N+M  
GOTO 200

CONTINUE  
N=N+M  
GOTO 200

INPUT value of dielectric constant...

INPUT value of dielectric constant...

INPUT value of dielectric constant...

IF(POL(I)) .EQ. '+'GOTO 4260  
A(J)=1.0  
B(I)=0.0  
CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE
4470 4490 GOTO 4490
4480 C=10.0/9.*LN
CONTINUE
PRINT('T2,9,F10.4,A)', 'INDUCTANCE OF CIRCUIT IS L=',LN,'nH/m'
PRINT('T2,9,F10.4,A)', 'CAPACITANCE IS C=',C,'nF/m'
PRINT('T2,9,F10.4,A)', 'CHAR. IMPED. IS Z=',SQRT(L/C),'ohms'
PRINT('T2,9,F10.4,A)', 'TOTAL CROSS-SECTIONAL AREA IN ONE DIRECTION IS A=',A,'sq. mm'
PRINT('(',')
PRINT('T2,9,F10.4,A)', 'TOTAL CROSS-SECTIONAL AREA IN ONE DIRECTION IS A=',A,'sq. mm'
PRINT('(',')
CONTINUE
DO 4640 I=1,N-1
IF(REC(I).EQ.1) GOTO 4600
CONTINUE
PRINT('(',')
CONTINUE
GOTO 4640
CONTINUE
PRINT('(',')
CONTINUE
GOTO 4640
CONTINUE
PRINT('(',')
CONTINUE
GOTO 200
CONTINUE
6000 PRINT*, 'Check individual conductors'
PRINT*', 'Input number of 1st conductor to be checked...
READ*, J
PRINT*, 'Input number of last conductor to be checked...
READ*, K
CONTINUE
DO 4200 I=J,K
IF(S(I).EQ.1) GOTO 4600
PRINT*, '(',')
CONTINUE
4200 PRINT*, 'Check another conductor? (1=yes, 0=no)...
READ*, U
IF(U.EQ.1) GOTO 6000
IF(U.EQ.0) GOTO 200
CONTINUE
GOTO 6500
CONTINUE
7000 PRINT*, 'Are you sure you want to exit program?
PRINT*, 1=YES,
PRINT*, 2=NO
READ*, U
IF(U.EQ.1) GOTO 200
IF(U.EQ.0) GOTO 7500
CONTINUE
GOTO 7000
CONTINUE
7500 END
PROGRAM LAPLAC

* specifications
INTEGER NMIN,NMAX,MINN,MMAX
INTEGER P(0:64,0:64),L
INTEGER N1,N2,N3,N4,M1,M2,NS,MS
INTEGER LMAX,LS,OUT,IN,ID,JD,LT
INTEGER I,J,K,KD,KQ,KT,KMAX,JSL,MM2,MM3,M2SL,RPN1,RPM1
REAL ERLIM,ACAP,DCAP,RPA,RPB,RPC
REAL FCO(0:64,0:64),C(0:18,1:5),H,RP1,RP2
CHARACTER P5(0:18)*1
COMMON/F,P,C,L,H,RP1,RP2
COMMON/RELAX/LAMBDA,ERMAX,NM,NMAX,MMIN,MMAX

* initializations
DATA N,M,NMIN,NMAX,MMIN,MMAX/32,64,0,20,0,48/
DATA ERLIM,KMAX/1E-4,100/
DATA N1,N2,N3,N4,M1,M2,NS,MS/4,12,16,4,16,32,6,18/
DATA (P5(I),I=0,18)*1
DATA LAMBDA,LHAX,H/1.4,4,0.125/
DATA RP1,RP2,RPN1,RPM1,KO,KT/1,1,16,32,0,0/

* function statements
IRNOCF1=NINT(F1*1E3)

* data inputs
PRINT"(A)\"OUTPUT TYPE (0=ALL, 1=FINAL, 2=DATA FILE)\""
READ*,OUT
PRINT"(A)\"INPUT TYPE (0=INTERNAL,1=EXTERNAL,2=DATA FILE)\""
READ*,IN
IF(IN.EQ.2) THEN
READ"(3I3,2F6.3)*N,M,L,H,SL"
DO 2 ID=0,M
DO 1 ID=0,N
READ"(2I3,E15.7,I3)*I,J,F(ID,JD),P(ID,JD)"
1 CONTINUE
2 CONTINUE
CALL CNTOUR
GOTO 999
ENDIF
IF(IN.LE.1) THEN
PRINT"(A)\"INPUT SLOPE (0=0.5,1,2,3=NO FLAP )\""
READ*,SL
ENDIF
3 PRINT"(/T2,A,F6.3,/,A//10A5,2A8)\"
: "BOUNDARY DIMENSIONS( 1 = 'H', mm)\"
: N1,N2,N3,N4,M1,M2,NS,MS,SLOPE,LAMBDA
IF(IN.LE.1) GOTO 4
READ*N,M,N1,N2,N3,N4,M1,M2,NS,SL,LAMBDA
4 PRINT"(10I5,2F8.3)\"N,M,N1,N2,N3,N4,M1,M2,NS,MS,SL,LAMBDA"
PRINT"(13,A,/,4A6)\"
: "INPUT CONTOUR LIMITS" NMIN,NMAX,MMIN,MMAX
IF(IN.LE.1) GOTO 5
READ*NMIN,NMAX,MMIN,MMAX
5 PRINT"(/I6)\"NMIN,NMAX,MMIN,MMAX"
*boundary conditions--------------------------------------------
PRINT '(A)', 'HOMOGENEOUS DIELECTRIC CONSTANT(YES=GE(1), NO=LE(-1))'
READ*, RP1
IF(RP1 .GT. 0) THEN  
  KD=0  
  RP2=RP1  
  RP1=1.0  
ELSE  
  RP2=ABS(RP1)  
  RP1=1.0  
  KD=0
PRINT'(A)', 'DIELECTRIC CONFIGURATION(1=INSIDE, 2=OUTSIDE)'
READ*, KD
IF(KD .EQ. 1) THEN
  KT=0
  PRINT'(A)', 'DISTANCE FROM CENTER?'
  READ*, KT
  RPM1=M1+KT  
  RPN1=N3
ELSE
  PRINT'(A)', 'OUTSIDE LAYER THICKNESS?'
  READ*, KT
  RPM1=N3+KT  
  RPN1=M2+KT
ENDIF
ENDIF
RPA=2*RP1  
RPB=2*RP2  
RPC=RP1+RP2
*point type, array setup----------------------------------------
*homogeneous interior point---------------------------------------
DO 7 J=1,5
  C(5,J)=RPA
7 CONTINUE
DO 8 J=1,5
  C(6,J)=RPB
8 CONTINUE
*dielctric in two adjacent quadrants -----------------------------
C(7,1)=RPC  
C(7,2)=RPC  
C(7,3)=RPA  
C(7,4)=RPB  
C(7,5)=RPC*2  
C(8,1)=RPA  
C(8,2)=RPB  
C(8,3)=RPC  
C(8,4)=RPC  
C(8,5)=RPC*2  
C(9,1)=RPC  
C(9,2)=RPC  
C(9,3)=RPB  
C(9,4)=RPA  
C(9,5)=2*RPC  
C(10,1)=RPA  
C(10,2)=RPB  
C(10,3)=RPC  
C(10,4)=RPC
*dielectric in one quadrant-------------------
C(10,1) = RPA
C(11,1) = RPA
C(11,2) = RPC
C(11,3) = RPA
C(11,4) = RPC
C(12,1) = RPA
C(12,2) = RPC
C(12,3) = RPA
C(12,4) = RPC
C(13,1) = RPC
C(13,2) = RPA
C(13,3) = RPC
C(13,4) = RPA
C(13,5) = RPC + RPA
C(14,1) = RPC
C(14,2) = RPA
C(14,3) = RPC
C(14,4) = RPA
C(14,5) = RPC + RPA

*dielectric in three quadrants----------------
C(15,1) = RPC
C(15,2) = RPA
C(15,3) = RPA
C(15,4) = RPC
C(16,1) = RPC
C(16,2) = RPA
C(16,3) = RPA
C(16,4) = RPC
C(16,5) = RPC + RPA
C(17,1) = RPC
C(17,2) = RPA
C(17,3) = RPA
C(17,4) = RPC
C(17,5) = RPC + RPA
C(18,1) = RPC
C(18,2) = RPA
C(18,3) = RPA
C(18,4) = RPC
C(18,5) = RPC + RPA

*initial point type------------------------
DO 10 I = O, N
   DO 9 J = 0, N
      F(I, J) = 0.0
      D(I, J) = RPA
      P(I, J) = 5
   9 CONTINUE

*defined boundaries-----------------------
DO 600 L = 2, 0, -1
   L = (2 * N - 1) / L
   K0 = KMAX / REAL(L)

*upper boundary (x=y=m)-------------------
DO 15 I = 0, N, L
   P(I, M) = 2
10 CONTINUE
15 CONTINUE
Continued

* right boundary \((x=n', y)\)
  DO 20 J=0, M*L
  P(N', J) = 2
  CONTINUE

* lower dielectric boundary \((x, y=0)\)
  DO 30 I=(N'+L), (N'-L), L
  P(I, 0) = 3
  CONTINUE
  DO 35 I=(N'+L), N', L
  P(I, 0) = 3
  CONTINUE

* left dielectric boundary \((x=0, y)\)
  DO 40 J=(M'+L), M, L
  P(0, J) = 4
  CONTINUE

* defined conductors

* center conductor \((x, y)\)
  DO 50 I=0, N'+L
  F(I, J) = 1.0
  P(I, J) = 1
  CONTINUE

* outer conductor \((x, y)\)
  DO 60 I=N'+N, N, L
  P(I, J) = 2
  CONTINUE

* outer conductor edge \((x, y)\)
  IF(SL.GT.2) GOTO 80
  MM2=M2-LMAX
  MM3=M2+5*LMAX
  DO 75 J=MM2, MM3, L
  I=N3, N, J
  JSL=NINT1*(N2-11)/L/M2SL=M2+JSL
  IF((M2SL-(N3-N2+L) .LT. J .AND. J .LE. M2SL) .OR. (N2 .LE. I .AND. J .LT. M2SL)) THEN
    F(I, J) = 0.0
    P(I, J) = 2
  ELSE
    P(I, J) = 5
  ENDIF
  CONTINUE

* second dielectric fill
  IF(KD.GT.0) THEN
    DO 140 J=1, (RPM1-L)
    DO 120 I=1, (RPN1-L)
      IF(P(I, J) .GT. 4) THEN
        P(I, J) = 6
      ENDIF
      IF(KD.EQ.2) THEN
        P(RPN1, J) = 8
      ENDIF
      CONTINUE
      DO 140
      CONTINUE
DO 160 I=1,(RPN1-1)
  IF(P(I,RPM1).GT.4)THEN
    P(I,RPM1)=7
  ENDIF
CONTINUE
160
IF(KD.EQ.2)THEN
  P(RPN1,RPM1)=11
ENDIF
ENDIF

*air pocket location----------------------------------------
IF(L.GT.1)GOTO 180
170
PRINT'(A)·,'lNPUT
AIR POCKET LOCATION(I,J),(-1,X)=NONE'
READ*,I,J
LT=1
IF(I.GT.0)THEN
  P(I,J)=5
  P(I-LT,J)=5
  P(I+LT,J)=5
  P(I,J-LT)=5
  P(I,J+LT)=5
  P(I+LT,J-LT)=7
  P(I,J-2*LT)=9
  P(I+2*LT,J)=10
  P(I-LT,J+LT)=11
  P(I,J+1)=12
  P(I,J+2*LT)=13
  P(I+2*LT,J+L)=14
  P(I-LT,J+L)=15
  P(I,J+3*LT)=16
  P(I,J+3*LT)=17
  P(I+2*LT,J+L)=18
  P(I,J+2*LT)=18
GOTO 170
ENDIF

*point type printout--------------------------------------
180
IF(OUT.EQ.1)AND.L.GT.1GOTO 200
IF(OUT.GT.1)GOTO 200
PRINT'(T2,A//MESH SIZE =L'
PRINT'(T5,A//V=1000, *:V=0,B*Dy=0, *:dV/dx=0'
DO 190 J=M+0-L
  PRINT'(T6,33A)*(PS(P(I,J)),I=0,N,L)
190
CONTINUE
PRINT'(////)'
200
CONTINUE

*lambda loop---------------------------------------------
*iterate solution------------------------------------------
DO 230 K=1,KQ
  IF(K.EQ.1)THEN
    ERMAX=1
  ELSE
    ERMAX=0
  ENDIF
DO 220 J=0,M-L
DO 210 I=0,N-L
CALL PTCALC
CONTINUE
210 CONTINUE
CONTINUE
IF(ERMAX .LE. ERLIM) GOTO 240
K=0
240 CONTINUE
IF(L .LE. 1 .OR. OUT .LT. 1) THEN
CALL CAPC(NS,MS,ACAP,DCAP)
ENDIF
*~M~put ~~~~~l;!EQ:-2)GOTO-;OO----------~----------------------------------
IF(CL .GT. 1 .AND. OUT .GT. 0) GOTO 600
IF(K .EQ. 0) THEN
320 PRINT'(T2,A,IA,A,/)', 'SOLUTION HAS NOT CONVERGED
IN', KQ, ' ITERATIONS'
ELSE
PRINT'(T2,A,IA,A,/)', 'SOLUTION CONVERGED AFTER', K, ' ITERATIONS'
ENDIF
PRINT'(T2,A,F9.6,/)', :
PRINT'(T2,A,A,F9.6,/)', :
PRINT'(T2,A,F10.6,A/)·,'CORNER CAPACITANCE (AIR) =',ACAP,'pF/m'
PRINT'elllllllllllll)
*solution array printout---------------------------------------------------
IF(LS .LT. 1) THEN
400 PRINT'(T2,A/)','SOLUTION AT n*m POINTS, (x=horiz, y=vert):
DO 400 J=M,0,-L
PRINT'(T2,33(I4))',(IRND(f(I,J)),I=0,N,L)
CONTINUE
PRINT'(T2,A,A/T2,A/)'
ENDIF
GOTO 600
*data file output-------------------------------------------------------
500 IF(L .EQ. 1) THEN
PRINT'(3I3,2F6.3)',N,M,L,H,SL
DO 520 J=0,M
DO 510 I=0,N
PRINT'(2I3,E15.7,I3)',I,J,f(I,J),P(I,J)
CONTINUE
520 CONTINUE
510 CONTINUE
PRINT'(I3)*,-1
GOTO 999
*termination--------------------------------------------------------------
600 CONTINUE
PRINT'(I1A/,A,IIII)','CHANGE PARAMETERS? (-1 TO END, 1=FLAP SLOPE, 2=LAMBDA, 3=BOUNDARY CONDITIONS)
READ'(I3)' I
IF(I .LT. 0) GOTO 999
GOTO(620,630,640),I
SUBROUTINE PTtALt
* specifications ------------------------------------------------------
INTEGER I, J, PK
INTEGER PO:64,0:64), L
REAL F1,F2,F3,F4,F5,F6,F7,F8
REAL C1,C2,C3,C4,C5
REAL PAST, Temp, ER, FINT, fNORM, FDIEL
REAL ERMAX-LAMBDA
REAL FCO:64,0:64), C(O:18,1:5), H, RP1, RP2
COMMON F,P,C,L,H,RP1,RP2
COMMON/RELAX/LAMBDA,ERMAX,I,J
* function statements ------------------------------------------------
FINTCF1,F2,F3,F4,F5,F6,F7,F8)=(4*(F1+F2+F3+F4)+(F5+F6+F7+F8))*.05
FNORM(F1,F2)=(4*F1+F2)/3
FDIEL(F1,F2,F3,F4,C1,C2,C3,C4,C5)=(C1*F1+C2*F2+C3*F3+C4*F4)/(2*C5)
* relaxation ---------------------------------------------------------
120 TEMP=FNORM(f(I,(2*L)),F(I,L)) GOTO 190
140 TEMP=FNORM(f(I+L,J),F(L,J)) GOTO 190
160 TEMP=FDIEL(F(I+L,J),F(I,J),F(I,J),F(I,J)),F(I,J),F(I,J),F(I,J),F(I,J))
190 PAST=F(I,J) F(I,J)=PAST+LAMBDA*(TEMP-PAST)
195 ER=ABS(PAST-F(I,J)) ERMAX=MAX(ERMAX,ER)
RETURN
END
************************************************************************
SUBROUTINE CAPCTCNS, MS, ACAP, DCAP)
* specifications -----------------------------------------------
INTEGER NS, MS
INTEGER PO:64,0:64), L
REAL ENORM, PERMFS, ACAP, DCAP
REAL FCO:64,0:64), C(O:18,1:5), H, RP1, RP2
PARAMETER (PERMFS=8.85419)
* surface integration ------------------------------------------
ENORM=0.0
ENORM=ENORM+F(NS+L)+F(NS-L)+F(NS+M)+F(NS-M)+F(NS,L)+F(NS,M)+F(NS,L)+F(NS,M)+F(NS,L)+F(NS,M)
DO 10 J=L,MS,MS
10 CONTINUE
SUBROUTINE PTCALC
* specifications ------------------------------------------------------
INTEGER I, J, PK
INTEGER PO:64,0:64), L
REAL F1,F2,F3,F4,F5,F6,F7,F8
REAL C1,C2,C3,C4,C5
REAL PAST, Temp, ER, FINT, fNORM, FDIEL
REAL ERMAX-LAMBDA
REAL FCO:64,0:64), C(O:18,1:5), H, RP1, RP2
COMMON F,P,C,L,H,RP1,RP2
PARAMETER (PERMFS=8.85419)
DO 20 I=L,(NS-L),L
    ENORM=ENORM+F(I,MS+L)-F(I,MS-L)
CONTINUE
ACAP=ABS((SE-4*PERMFS*(NS+MS)*ENORM)/H)
DCAP=RP2*ACAP
RETURN
END
************************************************************************

SUBROUTINE CNTOUR

*specifications-----------------------------------------------
INTEGER IR,IC,NCOL,MROW,MARKX,MARKY
INTEGER I,J,NO,MO,DN,DM,PD
INTEGER NMIN,NMAX,MMIN,MMAX
INTEGER P(0:64,0:64),L
REAL F(0:64,0:64),C(0:18,1:5),H,RP1,RP2
CHARACTER DARY(0:132,0:260),1,CS(0:16)*1
COMMON F,P,C,L,H,RP1,RP2
COMMON/CONTOR/NMIN,NMAX,MMIN,MMAX
COMMON/CHRSET/DARY,CS
COMMON/INTSET/I,J,NO,MO,DN,DM,PD

*initializations-----------------------------------------------
DATA NCOL, MROW, MARKX, MARKY /128, 256, 5, 4/
DATA DN, DM /5, 4/
DATA (CS(I),I=0,16) /'O', 'I', '2', '3', '4', '5', '6', '7', '8', '9', '0', '+', '.', ',', '-', ' ' /

*character array clear----------------------------------------
DO 20 IR=0,MROW
    DO 10 IC=0,NCOL
        DARY(IC,IR)=CS(15)
    CONTINUE
CONTINUE

*character array fill-----------------------------------------
DO 40 J=MMIN,MMAX
    DO 30 I=NMIN,NMAX
        NO=(I-NMIN)*DN
        IF(P(I,J) .LT. 3) THEN
            PD=(-P(I,J))
            CALL CHRFL
        ELSE
            IF(I .GT. NMIN) THEN
                IF(P(I-L,J) .LT. 3) THEN
                    PD=1
                    CALL CHRFL
                ENDIF
            ELSE
                IF(P(I,J-L) .LT. 3) THEN
                    PD=2
                    CALL CHRFL
                ENDIF
            ENDIF
        ENDIF
    CONTINUE
CONTINUE
30 CONTINUE
*print character array---------------------------------------------
DO 50 IR=(NMAX-MIN)*DN,0,L
PRINT*(132A1),(DARY(IC,IR),IC=0,(NMAX-MIN)*DN)
50 CONTINUE
RETURN
*************************************************************************
SUBROUTINE CHRFIL
*specifications--------------------------------------------------------
INTEGER CF,i,LJ
INTEGER I,J,NO,MO,DN,DM,PD
INTEGER P(0:64,0:64),L
REAL FS,RMIN,RMIN,RMAX,NX,MY,MPN
REAL F(0:64,0:64),C(0:18,1:5),H,RP1,RP2
CHARACTER DARY(0:132,0:260)*1,CS(0:16)*1
COMMON F,P,C,L,H,RP1,RP2
COMMON/CHRSET/DARY,CS
COMMON/INTSET/I,J,NO,MO,DN,DM,PD
*initializations------------------------------------------------------
DATA RMIN,RMIN,RMAX/0.01,0.05,0.95/
*character array DN*DM segment fill-----------------------------------
LI=L
LJ=L
IF(PD.LT.0)THEN
   CF=(10-PD)
   DARY(NO,MO)=CS(CF)
   GOTO 99
ELSE
   IF(PD.EQ.1)THEN
      LI=-L
   ELSE
      IF(PD.EQ.2)THEN
         LJ=-L
      ENDIF
   ENDIF
ENDIF
ENDIF
ENDIF
DO 30 M=0,(1)11-1)
DO 20 N=0,(ON-1)
   IF(P .GE. 0)THEN
      IF((N+H) .LT. 1)THEN
         FS=F(I,J)
      ELSE
         NX=N/REAL(DN)
         MY=M/REAL(DM)
         MPN=NX*MY
         FS=F(I,J)*(1.0+MPN-NX-MY)+F(I+LI,J)*(NX-MPN)+
         F(I,J+LJ)*(MY-MPN)+F(I+LI,J+LJ)*MPN
      ENDIF
      IF(FS .LT. RMIN)THEN
         CF=16
      ELSE IF(FS .LT. RMIN .OR. FS .GT. RMAX)THEN
         CF=10
      ELSE
IF (FS .GE. 0.999) THEN
    CF = INT (FS * 10)
ELSE
    CF = NINT (FS * 10)
ENDIF
ENDIF
ENDIF
ENDIF
10  DARY (NO + N*LI, MO + M* LJ) = CS (CF)
20  CONTINUE
30  CONTINUE
99  RETURN
END

*===========================================================================
REFERENCES


### TABLE I. - CHARACTERISTIC IMPEDANCE AND INDUCTANCE OF DOUBLE LAYER MULTICONDUCTOR LINES ("INDUCTANCE" METHOD)

<table>
<thead>
<tr>
<th>Number of wires</th>
<th>R₁, mm</th>
<th>R₂, mm</th>
<th>R₁, mm</th>
<th>θ, deg</th>
<th>Z, Ω</th>
<th>L, nH/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>78.5</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>0.5</td>
<td>45</td>
<td>88.7</td>
</tr>
<tr>
<td>16</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>36.2</td>
</tr>
<tr>
<td>16</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>0.5</td>
<td>25.5</td>
<td>37.4</td>
</tr>
<tr>
<td>32</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>15.2</td>
</tr>
<tr>
<td>64</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>5.9</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>25</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>65.6</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>25</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>28.6</td>
</tr>
<tr>
<td>32</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>1.0</td>
<td>0</td>
<td>33.1</td>
</tr>
<tr>
<td>32</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>2.0</td>
<td>0</td>
<td>11.7</td>
</tr>
<tr>
<td>32</td>
<td>25</td>
<td>50</td>
<td>1.0</td>
<td>2.0</td>
<td>0</td>
<td>10.3</td>
</tr>
<tr>
<td>64</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>2.0</td>
<td>0</td>
<td>4.1</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>25</td>
<td>0.5</td>
<td>4.0</td>
<td>0</td>
<td>17.2</td>
</tr>
<tr>
<td>32</td>
<td>10</td>
<td>25</td>
<td>1.0</td>
<td>4.0</td>
<td>0</td>
<td>4.3</td>
</tr>
</tbody>
</table>

### TABLE II. - Z₀ AND L OF DOUBLE RING MULTICONDUCTOR LINES ("CAPACITANCE" METHOD)

<table>
<thead>
<tr>
<th>R₁, mm</th>
<th>R₂, mm</th>
<th>θ, deg</th>
<th>r, mm</th>
<th>Total number of wires in line, N</th>
<th>Z₀, Ω</th>
<th>L, nH/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>8</td>
<td>73.5</td>
<td>371.5</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>8</td>
<td>83.7</td>
<td>423.0</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>16</td>
<td>33.7</td>
<td>170.0</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>16</td>
<td>34.9</td>
<td>176.5</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>32</td>
<td>13.9</td>
<td>70.5</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>32</td>
<td>10.4</td>
<td>52.6</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>32</td>
<td>6.6</td>
<td>33.3</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>32</td>
<td>0.22</td>
<td>1.09</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>64</td>
<td>3.3</td>
<td>16.8</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0.5</td>
<td>64</td>
<td>.17</td>
<td>.88</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>0</td>
<td>1</td>
<td>64</td>
<td>18.7</td>
<td>94.4</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>0</td>
<td>0.5</td>
<td>64</td>
<td>9.6</td>
<td>48.6</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>0</td>
<td>1</td>
<td>32</td>
<td>5.4</td>
<td>27.6</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>0</td>
<td>0.5</td>
<td>64</td>
<td>3.0</td>
<td>15.1</td>
</tr>
</tbody>
</table>
### TABLE III. - 64-WIRE, 5-RING TRANSMISSION LINES

<table>
<thead>
<tr>
<th>Ring in ring</th>
<th>Coordinates (1st)</th>
<th>Polarity (1st)</th>
<th>Ring polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R, mm</td>
<td>r, deg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line 1 (all radii the same #18 AWG)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>0.51</td>
<td>2.6393</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td></td>
<td>4.6593</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td></td>
<td>6.6793</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td></td>
<td>8.6993</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td></td>
<td>10.7193</td>
</tr>
</tbody>
</table>

| Line 2 (five different wire sizes) |
| 1            | 8                 | 0.3            | 2.6393       | 0             | +             | Alt.         |
| 2            | 8                 | .51            | 4.6593       | 0             | -             | Alt.         |
| 3a           | 4                 | .27            | 6.6793       | 0             | +             | Same         |
| 3b           | 8                 | .45            |              | 22.5          | -             | Same         |
| 3c           | 4                 | .51            |              | 45            | +             | Same         |
| 4a           | 4                 | .45            | 8.6993       | 0             | -             | Same         |
| 4b           | 8                 | .35            |              | 22.5          | +             | Same         |
| 4c           | 4                 | .3             |              | 45            | -             | Same         |
| 5            | 16                | .51            | 10.7193      | 0             | +             | Alt.         |

**DATA OUTPUT**

<table>
<thead>
<tr>
<th></th>
<th>Line 1</th>
<th>Line 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$, nH/m</td>
<td>15.33</td>
<td>18.70</td>
</tr>
<tr>
<td>$C$, nF/m</td>
<td>1.67</td>
<td>1.37</td>
</tr>
<tr>
<td>$Z$, $\Omega$</td>
<td>3.03</td>
<td>3.70</td>
</tr>
<tr>
<td>$A$, mm²</td>
<td>26.15</td>
<td>18.95</td>
</tr>
</tbody>
</table>
### TABLE IV. - RECOMMENDED WIRE ARRANGEMENTS FOR POWER LINE

<table>
<thead>
<tr>
<th>Number</th>
<th>Wire size (#AWG)</th>
<th>Total number of wires</th>
<th>Ranges of values inductance, nH/m</th>
<th>Characteristic impedance, Ω</th>
<th>Resistance, Ω</th>
<th>Weight of copper, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>80</td>
<td>6.3</td>
<td>10.4</td>
<td>1.2</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>52</td>
<td>9.7</td>
<td>16.0</td>
<td>1.8</td>
<td>3.2</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>104</td>
<td>4.8</td>
<td>8.0</td>
<td>0.9</td>
<td>1.6</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>132</td>
<td>3.8</td>
<td>6.3</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>208</td>
<td>2.4</td>
<td>4.0</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>256</td>
<td>2.0</td>
<td>3.2</td>
<td>0.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

### TABLE V. - DC AND AC RESISTANCE AND WEIGHT FOR MINIMUM NUMBER OF WIRES PER LINE

[Line Length, 150 m (total length for resistance calculation is 300 m), i.e., wires/direction.]

<table>
<thead>
<tr>
<th>Number AWG</th>
<th>Minimum number of wires/line</th>
<th>R_{dc}, Ω</th>
<th>R_{ac}, Ω</th>
<th>R_p, Ω*</th>
<th>Weight, kg**</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>26</td>
<td>0.242</td>
<td>0.249</td>
<td>0.349</td>
<td>57.1</td>
</tr>
<tr>
<td>21</td>
<td>52</td>
<td>0.242</td>
<td>0.244</td>
<td>0.342</td>
<td>57.0</td>
</tr>
<tr>
<td>22</td>
<td>65</td>
<td>0.244</td>
<td>0.245</td>
<td>0.343</td>
<td>56.4</td>
</tr>
<tr>
<td>33</td>
<td>833</td>
<td>0.244</td>
<td>0.244</td>
<td>0.342</td>
<td>56.4</td>
</tr>
<tr>
<td>36</td>
<td>1670</td>
<td>0.244</td>
<td>0.244</td>
<td>0.342</td>
<td>56.4</td>
</tr>
</tbody>
</table>

*R_p includes proximity effects.  
**Weight (copper alone).
Figure 1. - Current distribution in a circular cylindrical wire of radius $r_0$ at 20 kHz.

Figure 2. - Polar coordinates for CRIMPD.F, single-ring arrangement.
Figure 3. - Polar coordinates for CRIMPD,F, double-ring arrangement.

Figure 4. - Parameter definition for equation (5). The direction of currents in the primed conductors is opposite to that in the unprimed.
Figure 5. - 64-Wire, 5-ring line 2 (inductance values in nH/m).

Figure 6. - 80-Wire (4x20) configuration. (All dimensions in inches.) For \( \varepsilon_r = 2.3, L = 10.42 \text{ nH/m}, C = 2450 \text{ pF/m}, \) and \( Z = 2.06 \Omega. \)
Scale: 0.2 inch = 1 mm.
Table:

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Line</th>
<th>(x_L), mm</th>
<th>(y_L), mm</th>
<th>Polarity</th>
<th>Number of conditions</th>
<th>Spacing, mm</th>
<th>Line polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 20</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>20</td>
<td>2</td>
<td>Alt.</td>
</tr>
<tr>
<td>21 to 40</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41 to 60</td>
<td>3</td>
<td>4</td>
<td>+</td>
<td></td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>61 to 80</td>
<td>4</td>
<td>6</td>
<td>-</td>
<td>2</td>
<td>Alt.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7. - 80-Wire (4x20) configuration with listing of individual self inductances in \(nH/m\) ("Inductance" method). \(L = 10.4196\ nH/m; C = 2.4526\ nF/m; Z = 2.0611\ \Omega; A = 32.6851\ mm^2; r = 0.51\ mm (\#18 AWG)."

Figure 8. - 80-Wire line ("Capacitance method") individual inductances. \(L = 6.3115\ nH/m; C = 4.0490\ nF/m; Z_0 = 1.2650\ \Omega; A = 32.08\ mm^2; r = 0.51\ mm (\#18 AWG)."

31
### Table

<table>
<thead>
<tr>
<th>Condition</th>
<th>$x_1$, mm</th>
<th>$y_1$, mm</th>
<th>Spacing, mm</th>
<th>Polarity</th>
<th>Line Radii, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 32</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>33 to 64</td>
<td></td>
<td></td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>65 to 96</td>
<td></td>
<td></td>
<td>2.0</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>97 to 128</td>
<td></td>
<td></td>
<td>3.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>129 to 160</td>
<td></td>
<td></td>
<td>4.0</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>161 to 192</td>
<td></td>
<td></td>
<td>5.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>193 to 224</td>
<td></td>
<td></td>
<td>6.0</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>225 to 256</td>
<td></td>
<td></td>
<td>7.0</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 9.** 256-wire (8x32) arrangement with individual self inductances in nH/m. $L = 3.2193$ nH/m; $C = 7.9382$ nF/m; $Z = 0.6368$ $\Omega$; $A = 25.1327$ mm$^2$; $r = 0.25$ mm; $c_f = 2.3$. 

---

**Actual size**
Figure 10. - Male-female junction boxes with conventional outlets.
300 Isometric view
(a) High frequency power distribution buss. Top cover not shown; material: chassis 0.063 Al-Alloy 5053; scale, 1/2.

(b) Junction-box detail. (All dimensions in inches.)

Figure 11. - Junction box.
Figure 12. - Cross section of a multiple-plate transmission line. \( L = 0.66 \text{nF/m}; \ C = 35.3 \text{nF/m}; \ Z_0 = 0.14 \Omega; \ v_f = 2.1 \)

Figure 13. - Stripline configuration.
**Abstract**

A low inductance, low characteristic impedance transmission line was designed for a 20 kHz power distribution system. Several different conductor configurations were considered: strip lines, interdigitated metal ribbons, and standard insulated wires in multiwire configurations (circular and rectangular cylindrical arrangements). The final design was a rectangular arrangement of multiple wires of the same gauge with alternating polarities from wire to wire. This offered the lowest inductance per unit length (on the order of several nanohenries/meter) and the lowest characteristic impedance (on the order of one ohm). Standard multipin connectors with gold-plated elements were recommended with this transmission line; the junction boxes to be internally connected with flat metal ribbons for low inductance; and the line to be constructed in sections of suitable length. Computer programs for the calculation of inductance of multiwire lines and of capacitances of strip lines were developed.

---

### Key Words (Suggested by Author(s))

- High frequency aircraft power distribution
- Space power

---

**Distribution Statement**

Unclassified - unlimited

**STAR Category**

07

---

*For sale by the National Technical Information Service, Springfield, Virginia 22161*