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

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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} \( \Omega \)-m conductivity = 5.88x10^{7} mho/m) is 0.46 mm \( \approx \) 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} mho/m (ref. 6). As a consequence, the term \( RG/\omega^2 LC \) 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, $Z_0 = (L/C)^{1/2} \Omega$. 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)

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

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 $L = (Cv^2)^{-1} = \mu \varepsilon / L_0 = Z_0 \sqrt{\mu \varepsilon}$.

2.2 Inductance Calculations

In the following calculations, the permeability of all materials will be assumed to be that of free space ($\mu_0 = 4\pi \times 10^{-7}$ 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)

\[
L_{eq} = \left( \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{1}{L_{ij}} \right)^{-1} \text{H/m}
\]  \hspace{1cm} (4)

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

The FORTRAN program for this calculation, CRIMP.D.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

\[
L_a = \frac{\mu_0}{2\pi} \left( \frac{1}{2} + 2 \ln \frac{D_{aa'} \cdot D_{ab'} \cdot \ldots \cdot D_{an'}}{r_a \cdot D_{ab} \cdot D_{ac} \cdot \ldots \cdot D_{an}} \right) \text{H/m}
\]  \hspace{1cm} (5)

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

\[
L_{eq} = \left( \sum_{i=1}^{n} \frac{1}{L_i} \right)^{-1} + \left( \sum_{i=1}^{n} \frac{1}{L_i} \right)^{-1} \text{H/m}
\]  \hspace{1cm} (6)
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 \( D \))

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

so that the external self-inductance of one conductor is

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

because \( LC = \mu \epsilon \). 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, \( \mu / \epsilon \), 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 $21.15 \times 10^{-6}$ m². 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 mm²). 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 mm².

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 mm². 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 "zc").

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 $1.9 < Z_0 < 3.2 \text{ Q}$. 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 $1 \text{ kV/mm} = 1 \text{ MV/m} = 25 \text{ V/mil}$. 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

$$\frac{C}{G} = \epsilon/\sigma \quad (9)$$

which, for the materials under consideration, will be on the order of $10^{-15} \text{ mho/m}$ ($R$ of the order of $10^{15} \text{ Q/m}$), using $10^{17} \text{ Q-m}$ 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 Ω), 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 \( s \), 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 CRIMP_D.F

DOUBLEPRECISION A,E,C
DOUBLEPRECISION S(1:1024),O(1:1024),X(1:1024),Y(1:1024)
DOUBLEPRECISION L(0:1024),LO(0:1024),L1(0:1024),LN
DOUBLEPRECISION SA,SD,PI,SLOPEANG
INTEGER MAX,NUM,JE,ALTPOL
INTEGER U,J,N,RP(1:1024)
PARAMETER (PI=3.141592654)

100 QI="SELECTION IS OUT OF BOUNDS. TRY AGAIN..."
CONTINUE
DO 130 I=1,164
PRINT* S(I)=0. O(I)=0. X(I)=0.
Y(I)=0. UI=0. LO(I)=0. L1(I)=0. LN(I)=0.
T(I)=0. R(I)=0. B(I)=0. POL(I)=I
CONTINUE
N=1
PRINT'('"Main Menu"
PRINT" 1. Polar coordinate input"
PRINT" 2. Rectangular coordinate input"
PRINT" 3. Data file input"
PRINT" 4. Run inductance calculation (Skilling method)"
PRINT" 5. Run capacitance calculation (Cheng method)"
PRINT" 6. Check individual conductors"
PRINT" 7. Exit to shell"
PRINT" 8. Enter new configuration (reset index counter)"
PRINT'('"'
PRINT'('"Choose from 1 thru 8..."
READ",U
IFU.EQ.7)GOTO 7000
IFU.EQ.6)GOTO 6000
IFU.EQ.5)GOTO 5000
IFU.EQ.4)GOTO 4000
IFU.EQ.3)GOTO 3000
IFU.EQ.2)GOTO 2000
IFU.EQ.1)GOTO 1000
IFU.EQ.0)GOTO 0
PRINT* GOTO 200
250 PRINT'('"ROUTINE NOT OPERATIVE, CHOOSE ANOTHER MODE...")
GOTO 200

1000 Polar coordinate input
PRINT" 1. Automatic ring input"
PRINT" 2. Individual input"
PRINT" 3. Exit to main menu"
PRINT'('"Choose one..."
READ",U
IFU.EQ.1)GOTO 200
IFU.EQ.2)GOTO 1500
IFU.EQ.0)GOTO 1100
PRINT* GOTO 1000

1100 Auto polar ring
PRINT'("AUTO POLAR RING"
PRINT'("Input number of conductors in this ring...")
READ",M
SA=2.0*PI/REAL(M)
SD=SA*180.0/PI
PRINT*,'Input coordinates, radius and polarity of 1st conductor'
PRINT*,'Input these coordinates, radius and polarity of 1st conductor
in this ring (r(mm),theta(degrees),radius(mm),+ or -)'
READ(S,1110) S(N),H(N),R(N),POL(N)
FORMAT(F8.4,F8.4,F8.4,A1)
0(N)=T(N)*PI/180.0
S(N)=S(N)/1000.0
R(N)=R(N)/1000.0
X(N)=S(N)*COS(0(N))
Y(N)=S(N)*SIN(0(N))
NP(N)=0

1120 PRINT*('(/A)')'Choose polarity of wires...'
PRINT* 1. Alternating
2. All the same as 1st
3. Individually selected
4. Exit to last menu
READ*,U
IF(U. EQ. 1)GOTO 1200
IF(U. EQ. 2)GOTO 1180
IF(U. EQ. 3)GOTO 1160
IF(U. EQ. 4)GOTO 1000
PRINT*,Q1
GOTO 1120

1160 UUU=1
GOTO 1260
U=0
GOTO 1260
UU=U
GOTO 1260

1260 I=N+1,N+M-1
R(I)=R(N)
IF(UUU. NE. 1)GOTO 1300
R(I)=R(I-1)+SA
T(I)=T(I-1)+S0
X(I)=S(I)*COS(T(I))
Y(I)=S(I)*SIN(T(I))

1280 IF(UUU. NE. 1)GOTO 1300
PRINT('(/,T2,A,13,A,F8.5,2X,FB.4) Conductor',I,'with coords. ',S(I)*1000.0,T(I)
PRINT*,'Input polarity (+ or -)'
READ'(A)',POL(I)
IF(POL(I-1) .EQ. +)POL(I)=·'
IF(POL(I-1) .EQ. ·-)POL(I)=·'
CONTINUE
N=N+1
GOTO 200

1340 CONTINUE

* Individual polar input
1500 PRINT*,'Individual Polar Inputs'
PRINT*,'How many conductors in this series?' READ*,N
DO 1560 I=N+1,N+M-1
R(I)=R(I-1)+SA
T(I)=T(I-1)+S0
X(I)=S(I)*COS(T(I))
Y(I)=S(I)*SIN(T(I))
1560 CONTINUE

* Rectangular coordinate input
2000 PRINT*,'RECTANGULAR COORDINATE INPUT'
2100 PRINT*,'Choose one...'
PRINT* 1. Individual input
2. Line input (equally spaced wires)
3. Return to main menu
READ*,U
IF(U. EQ. 1)GOTO 2120
IF(U. EQ. 2)GOTO 2000
IF(U. EQ. 3)GOTO 200
PRINT,*,'Individual Rectangular Inputs'
READ=K
DO 2150 I=N+1,N+K-1
PRINT,*,'Input coordinates, radius & polarity of conductor ',I,'.'
READ(5,1110) X(I),Y(I),R(I),POL(I)
RP(I)=1
X(I)=X(I)/1000.0
Y(I)=Y(I)/1000.0
R(I)=R(I)/1000.0
S(I)=SQRT(X(I)**2+Y(I)**2)
IF(S(I) .EQ. 0.0) GOTO 2140
T(I)=180.0/PI*ACOS(X(I)/S(I))
GOTO 2150
T(I)=0.0
CONTINUE
N=N+K
GOTO 200

*AUTO LINE

PRINT,*,'AUTO LINE INPUT'
PRINT,*,'Input coordinates, radius & polarity of 1st conductor...'
READ(5,1110) X(N),Y(N),R(N),POL(N)
X(N)=X(N)/1000.0
Y(N)=Y(N)/1000.0
R(N)=R(N)/1000.0
S(N)=SQRT(X(N)**2+Y(N)**2)
IF(S(N) .EQ. 0.0) GOTO 2210
T(N)=180.0/PI*ACOS(X(N)/S(N))
GOTO 2230
T(N)=0.0
CONTINUE
RP(N)=1
PRINT,*,'Input number of conductors on this line...'
READ=K
PRINT,*,'Input distance between centers of cond. on this line (SPACING)...'
READ=SPACING
SPACING=SPACING/1000.0
PRINT,*,'Input slope angle of the line (positive x-axis=0 degrees)'
READ=SLOPEANG
SLOPEANG=SLOPEANG*PI/180.0
DO 2300 J=N+1,N+M-1
X(J)=X(J-1)+SPACING*COS(SLOPEANG)
Y(J)=Y(J-1)+SPACING*SIN(SLOPEANG)
R(J)=R(J-1)
S(J)=SQRT(X(J)**2+Y(J)**2)
T(J)=ACOS(X(J)/S(J))*180.0/PI
RP(J)=1
CONTINUE

PRINT,*,'Choose polarity of wires...'
READ=U
1. Alternating
2. All the same as the 1st
3. Individually selected
4. Return to last menu
IF(U .EQ. 1) GOTO 2340
IF(U .EQ. 2) GOTO 2380
IF(U .EQ. 3) GOTO 2420
IF(U .EQ. 4) GOTO 2000
PRINT=Q1
GOTO 2520

CONTINUE
IF(POL(N) .EQ. '+' ) THEN
ALTPOL=+1
ELSE IF(POL(N) .EQ. '-' ) THEN
ALTPOL=-1
END IF
DO 2360 J=N+1,N+M-1
IF(ALTPOL .EQ. 1) THEN
POL(J)=+2
ELSE IF(ALTPOL .EQ. -1) THEN
POL(J)=-2
END IF
ALTPOL=-ALTPOL
CONTINUE

2360...
2360 CONTINUE
N=N+M
GOTO 200
2380 CONTINUE
DO 2400 I=N+1,N+M-1
POL(I)=POL(N)
2400 CONTINUE
N=N+M
GOTO 200
2420 CONTINUE
DO 2400 I=N+1,N+M-1
PRINT*(7,'*2=A/13*17F8.5,2X,F8.4)"*<conductor*'I,'with coorden. x(mm)=',X(I),'y(mm)=',Y(I)
PRINT*"Input polarity (+ or -)...
CONTINUE
N=N+M
GOTO 200
2440 CONTINUE
PRINT*,CONDUCTOR,I,WITH COORDS.
X(MM)=X(I),Y(MM)=Y(I)
3000 CONTINUE
CONTINUE
D(O)=1.0
PRINT*,"Input value of dielectric constant...
READ*E
4050 CONTINUE
DO 4320 I=1,N-1
IF(POL(I).EQ."+")GOTO 4220
4220 CONTINUE
D(O)=1.0
DO 4280 J=1,N-1
IF(J.EQ. I)GOTO 4180
IF(J.EQ. I)GOTO 4180
D(J)=SQRT((X(J)-X(I))**2+(Y(J)-Y(I))**2)
D(J)=1.0/D(J)
GOTO 4280
4180 D(J)=D(J)*D(J-1)
4200 CONTINUE
GOTO 4300
4220 D(O)=1.0
DO 4280 J=1,N-1
IF(J.EQ. I)GOTO 4180
IF(J.EQ. I)GOTO 4180
D(J)=SQRT((X(J)-X(I))**2+(Y(J)-Y(I))**2)
D(J)=1.0/D(J)
GOTO 4280
4180 D(J)=D(J)*D(J-1)
4200 CONTINUE
GOTO 4300
4300 L(I)=COS**2.0+LOG(D(N-1)/R(I))*100.0
4320 CONTINUE
L(I)=0.0
L(I)=0.0
DO 4440 I=1,N-1
IF(POL(I).EQ."-")GOTO 4220
L(I)=1.0/L(I)
L(I)=0.0
GOTO 4420
L(I)=L(I)+L(I-1)
L(I)=L(I)+L(I-1)
4420 CONTINUE
L(I)=L(I)+L(I-1)
4440 CONTINUE
R(O)=0.0
DO 4480 I=1,N-1
R(I)=R(I)*1000.0
A=(R(I)**2+(R(I-1)**2
D(I)=SQRT(A)
4480 CONTINUE
A=A*D(I)**2
IF(AABS(L(N-1))<LE.0.00000001)GOTO 4480
LN=1.0/L(N-1)+1.0/L(N-1)
PRINT*(1X,J3,T15,F10.4,T36,F10.4,T53,A,T56,F10.4),I,S(I)*1000.0,f(I),POL(I),R(I)*1000.0,L(I)
GOTO 4640
CONTINUE
PRINT*(2X,I3,T7,T18,F10.4,T18,F10.4,T53,A,F10.4,T72,A),I,X(I)*1000.0,Y(I)*1000.0,POL(I),R(I)*1000.0,L(I)
GOTO 4700
CONTINUE
PRINT*,
'Are you sure you want to exit program?
PRINT*, 1=YES,
PRINT*, 2=NO
READ*, U
IFU.EQ.1 GOTO 6000
IFU.EQ.2 GOTO 7000
PRINT*,6000
GOTO 7000
END
PROGRAM LAPLAC

*specifications------------------------------------------------------
INTEGER NMIN, NMAX, MMIN, MMAX
INTEGER P(64, 64), L
INTEGER N, M, N2, N3, N4, M1, M2, NS, MS
INTEGER LMAX, LS, OUT, IN, ID, JD, LT
INTEGER I, J, K, KD, KT, KMAX, MM2, MM3, M2SL, RPN1, RPM1
REAL SL, ERLIM, ACAP, DCAP, RPA, RPB, RPC
REAL ERLIM, LAMBDA
REAL FC(64, 64), C(18, 5), H, RP1, RP2
CHARACTER P5(18) * 1
COMMON F, P, C, L, H, RP1, RP2
COMMON/LAPLAC/ LAMBDA, ERLIM, I, J
COMMON/RELAX/LAMBDA, ERLIM, I, J
COMMON/CONTOR/NMIN, NMAX, MMIN, MMAX

*initializations-----------------------------------------------------
DATA N, M, NMIN, NMAX, MMIN, MMAX / 32, 64, 20, 43/
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) *
:
:
:
:
:
:
:
:
:
:
:
:
:
:
:
:
:

READ*, OUT
PRINT'(A) INPUT TYPE (0 = INTERNAL, 1 = EXTERNAL, 2 = DATA FILE)'
READ*, IN
IF(IN .EQ. 2) THEN
READ*(313, 2F6.3)* N, M, L, H, SL
DO 2 ID = 0, M
DO 1 JD = 0, N
READ*(213, E15.7, I3), I, J, F(ID, JD), P(ID, JD)
1 CONTINUE
2 CONTINUE
CALL CNTOUR
GOTO 999
ENDIF
IF(IN .LT. 1) THEN
READ*(A) "INPUT SLOPE (0 = 0.5, 1 = NO FLAP):"
ENDIF
3 PRINT*(T2, A, F6.3) / 10A5, 2A8)"
: "BOUNDARY DIMENSIONS (1 = NS, 2 = SL, MM):"
IF(IN .LT. 1) GOTO 4
READ*N, M, N, N2, N3, N4, M1, M2, NS, MS, SL, LAMBDA
PRINT*(T15, 2F8.3)/* N, M, N, N2, N3, N4, M1, M2, NS, MS, SL, LAMBDA
PRINT*(T3, A, F4.6)"
: "INPUT CONTOUR LIMITS", "NMIN", "NMAX", "MMIN", "MMAX"
IF(IN .LT. 1) GOTO 5
READ*NMIN, NMAX, MMIN, MMAX
5 PRINT*(T46) / 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
*dielectric 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) = RPC
C(11, 1) = RPA
C(11, 2) = RPC
C(11, 3) = RPA
C(11, 4) = RPC
C(11, 5) = RPC + RPA
C(12, 1) = RPC
C(12, 2) = RPC
C(12, 3) = RPA
C(12, 4) = RPC
C(12, 5) = RPC + RPA
C(13, 1) = RPA
C(13, 2) = RPC
C(13, 3) = RPA
C(13, 4) = RPC
C(13, 5) = RPC + RPA
C(14, 1) = RPC
C(14, 2) = RPA
C(14, 3) = RPA
C(14, 4) = RPC
C(14, 5) = RPC + RPA

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

*initial point type-----------------------------
DO 10 I = 0, N
DO 9 J = 0, M
F(I, J) = 0.0
DC(I, J) = RP1
9 P(I, J) = 5
10 CONTINUE

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

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

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

*lower dielectric boundary (x,y=0)*
DO 30 I=(N1+L),(N2-L),L
P(I,0)=3
30 CONTINUE

*left dielectric boundary (x=0,y)*
DO 40 J=(M1+L),M,L
P(0,J)=4
40 CONTINUE

*defined conductors*
*center conductor (x,y)*
DO 50 I=0,N1,L
DO 55 J=0,M1,L
F(I,J)=1.0
50 CONTINUE

*outside conductor (x,y)*
DO 60 I=N2,N3,L
DO 65 J=0,M2,L
P(I,J)=2
60 CONTINUE

*outer conductor edge (x,y)*
IF(SL.GT.2)GOTO 80
MM2=M2-LMAX
MM3=M2+LMAX
DO 70 J=MM2,MM3,L
70 I=N3,N4,J
JSL=NINT(1*(N2-I)/L)/L
M2SL=M2+JSL
IF((M2SL-(N3-N2+L)) .LT. J .AND. J .LE. M2SL) .OR.
(N2 .LT. I .AND. J .LE. M2SL) THEN
F(I,J)=0.0
P(I,J)=5
ELSE
P(I,J)=2
ENDIF
70 CONTINUE

*second dielectric fill*
80 IF(KD.GT.0)THEN
DO 120 J=1,(RPM1-L)
DO 110 I=1,(RPN1-L)
IF(P(I,J).GT.4)THEN
P(I,J)=6
110 CONTINUE
ENDIF

120 CONTINUE
IF(KD.EQ.2)THEN
P(RPN1,J)=8
ENDIF
140 CONTINUE
DO 160 I=1,(RPN1-1)
  IF((P(I,RPM1)).GT. 4)THEN
    P(I,RPM1)=7
  ENDIF
160 CONTINUE
IF(KD .EQ. 2)THEN
  P(RPN1,RPM1)=11
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 .EQ. 0)THEN
  P(I,J)=5
  P(I+LT,J)=5
  P(I,J+LT)=5
  P(I,J-LT)-5
  P(I,J+2*LT)=7
  P(I,J+2*LT)=9
  P(I,J-2*LT)=10
  P(I,J-LT)=11
  P(I,J+LT)=12
  P(I,J-LT)=13
  P(I,J+2*LT)=14
  P(I,J-LT)=15
  P(I,J+2*LT)=16
  P(I,J+2*LT)=17
  P(I,J-2*LT)=18
  P(I,J-LT)=18
  GOTO 170
ENDIF
*point type printout---------------------------------------
180 IF(OUT .EQ. 1 .AND. L .GT. 1)GOTO 200
IF(OUT .EQ. 1)GOTO 200
PRINT'(12,A//"MESH SIZE =",L,
"BOUNDARY CONDITIONS":MESH SIZE =",L,
PRINT'(12,A//"MESH SIZE =",L,
DO 190 J=M,L
PRINT'(12,A//"MESH SIZE =",L,
DO 230 K=1,K0
  IF(K .EQ. 1) THEN
    ERMAX=1
  ELSE
    ERMAX=0
  ENDIF
DO 230 K=1,K0
  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
CALL PTCALC
CONTINUE
IF(ERMAX .LE. ERLIM)GOTO 240
CONTINUE
K=0
240 CONTINUE
IF(L .LE. 1 .OR. OUT .LT. L)THEN
CALL CAPCT(NS,MS,ACAP,DCAP)
ENDIF
*output analysis-----------------------------------------------
300 IF(OUT .EQ. 2)GOTO 500
310 IF(L .GT. 1 .AND. OUT .GT. 0)GOTO 600
320 IF(K .EQ. 0)THEN
PRINT'(T2,A,F9.6,/)', 'SOLUTION HAS NOT CONVERGED
IN',K,' ITERATIONS'
ELSE
PRINT'(T2,A,F9.6,/)', 'SOLUTION CONVERGED
AFTER',K,' ITERATIONS'
ENDIF
PRINT'CT2,A,F9.6,/)', 'WITH A
MAXIMUM ABSOLUTE ERROR OF',ERMAX
PRINT'(T2,A,F9.6,/)', 'STEP SIZE',LAMBDA
PRINT'(T2,A,F9.6,/)', 'MESH SIZE=',L,'*
STEP SIZE',LAMBDA
PRINT'(T2,A,F9.6,/)', 'CORNER CAPACITANCE (AIR) =',ACAP,'pF/m'
PRINT'!
*solution array printout-------------------------------------
350 IF(LS .LT. 1) THEN
PRINT'(T2,A/F9.6,/)', 'SOLUTION AT n*m
POINTS, (x=horiz, y=vert):'
DO 400 J=M,O,-L
PRINT'(T2,33I4,F6.3)',I,J,S(I,J),P(I,J)
CONTINUE
GOTO 600
400 IF(L .EQ. 1) THEN
PRINT'(3I3,2F6.3)',N,M,L,SL
DO 520 J=0,M-L
PRINT'(2I3,E15.7,I3)',I,J,F(I,J),P(I,J)
CONTINUE
PRINT'(13)*,-1
GOTO 999
500 IF(L .EQ. 1) THEN
PRINT'(3I3,2F6.3)',N,M,L,SL
DO 520 J=0,M-L
PRINT'(2I3,E15.7,I3)',I,J,F(I,J),P(I,J)
CONTINUE
520 PRINT'(13)*,-1
GOTO 999
510 ENDIF
*data file output---------------------------------------------
500 IF(L .EQ. 1) THEN
PRINT'(3I3,2F6.3)',N,M,L,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
510 PRINT'(13)*,-1
GOTO 999
520 ENDIF
*termination-----------------------------------------------
600 CONTINUE
PRINT'(A,A///)', 'CHANGE PARAMETERS? (-1 TO END, 1=FLAP SLOPE,
2=LAMBDA, 3=BOUNDRY CONDITIONS)
READ'(I3)' I
IF(I .LT. 0)GOTO 999
GOTO(620,630,640),I
SUBROUTINE PTtALt
*specifications------------------------------------------------------
INTEGER I,J,PK
INTEGER P(0:64,0:64),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 FCN:64,O: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))*0.05
FNORM(F1,F2)=(4*(F1+F2-F1)/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=FDIEL(C(I+L),J),F(I-L),J),F(I,J-L)
: C(CPK,1),C(PK,2),C(PK,3),C(PK,4),C(PK,5))
GOTO 190
160
TEMP=FINT(F(I-L,J),F(J-L),F(I-L,J),F(I,J-L)
: F(I+L,J),F(I,J+L),F(I-L,J-L))
180
TEMP=FINT(F(I-L,J),F(I-L,J),F(I,J-L),F(I,J-L)
: F(I+L,J),F(I,J+L),F(I-L,J-L))
190
PAST=F(I,J)
F(I,J)=PAST+LAMBDA*FINT-PAST
ER=ABS(F(I,J))
ERMAX=MAX(ERMAX,ER)
195 RETURN

END

*************************************************************************
SUBROUTINE CAPCTCNS,MS,ACAP,DCAP
*specifications-----------~--------------------------------------------
INTEGER NS,MS
INTEGER PCO:64,O:64),L
REAL ENORM,PERMFS,ACAP,DCAP
REAL F(O:64,O:64),C(O:18,1:5),H,RP1,RP2
COMMON F,P,C,L,H,RP1,RP2
PARAMETER (PERMFS=8.85419)

*surface integration---------------------------------------------------
ENORM=0.0
ENORM=ENORM+((F(NS+L-0)-F(NS+L-MS)-F(NS-MS+L+MS)+0.5
ENORM=ENORM+(F(NS+L-0)-F(NS+L-0)+F(NS+L+MS)-F(NS-MS+L+MS))+0.5
DO 10 J=LS,MS
ENORM=ENORM+F(NS+L,J)-F(NS-L,J)
10 CONTINUE
**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:S), 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, 41
DATA DN, DM, 5:4
DATA (CS(I), I=0, 16) /'0', '1', '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
   20 CONTINUE

*character array fill-----------------------------------------*

DO 40 J=MMIN, MMAX
   MO=(J-MMIN)*DM
   DO 30 I=NMIN, NMAX
      NO=(I-NMIN)*DN
      IF(P(I, J) .LT. 3) THEN
         PD=(-P(I, J))
         CALL CHRFIL
      ELSE
         IF(I .GT. NMIN) THEN
            IF(P(I-L, J) .LT. 3) THEN
               PD=1
               CALL CHRFIL
            ENDIF
         ELSE
            IF(P(I, J-1) .LT. 3) THEN
               PD=2
               CALL CHRFIL
            ENDIF
         ENDIF
      ENDIF
   CONTINUE
   30 CONTINUE
CONTINUE

*printing character array---------------------------------------------
DO 50 IR=(MMAX-MMIN)*DM,0,-L
PRINT*(132A1)'(DARY(IC,IR),IC=O,(MMAX-MMIN)*DN)
50 CONTINUE
RETURN

END

********************************************************************

SUBROUTINE CHRFIL

*specifications-----------------------------------------------------
INTEGER CF,I,LJ
INTEGER N,M
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(0:18,0:5),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/NO,MO,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
DO 30 M=0,(DM-1)
DO 20 N=0,(DN-1)
  IF(PD.GE.0)THEN
    IF((N+M).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+LI,J)*MPN
    ENDIF
    IF(FS.LT.RMIN)THEN
      CF=16
    ELSE IF(FS.GT.RMAX)THEN
      CF=10
    ELSE
      CF=10
    ENDIF
  ELSE
    IF((N+M).LT.1)THEN
      FS=F(I,J)
    ELSE
      FS=F(I,J)
    ENDIF
    IF(FS.LT.RMIN)THEN
      CF=16
    ELSE IF(FS.GT.RMAX)THEN
      CF=10
    ELSE
      CF=10
    ENDIF
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>R2, 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>
<td>396.8</td>
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<td>8</td>
<td>25</td>
<td>50</td>
<td>0.5</td>
<td>0.5</td>
<td>45</td>
<td>88.7</td>
<td>448.2</td>
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<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>
<td>182.9</td>
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<tr>
<td>16</td>
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<td>0.5</td>
<td>25.5</td>
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<td>0.5</td>
<td>0</td>
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<td>64</td>
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<td>0.5</td>
<td>0</td>
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<td>0.5</td>
<td>0</td>
<td>65.6</td>
<td>331.9</td>
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<td>0.5</td>
<td>0.5</td>
<td>0</td>
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<td>0.5</td>
<td>1.0</td>
<td>0</td>
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<td>2.0</td>
<td>0</td>
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<td>59.3</td>
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<tr>
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<td>10.3</td>
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<tr>
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<td>0.5</td>
<td>2.0</td>
<td>0</td>
<td>4.1</td>
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<tr>
<td>16</td>
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<td>0.5</td>
<td>4.0</td>
<td>0</td>
<td>17.2</td>
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<tr>
<td>32</td>
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<td>1.0</td>
<td>4.0</td>
<td>0</td>
<td>4.3</td>
<td>21.8</td>
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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>Zo, 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>
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<tr>
<td>25</td>
<td>45</td>
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<td>0.5</td>
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<td>83.7</td>
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<tr>
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<td>170.0</td>
</tr>
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<td>176.5</td>
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<td>0.5</td>
<td>32</td>
<td>6.6</td>
<td>33.3</td>
</tr>
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<td>25</td>
<td>4</td>
<td>0</td>
<td>0.5</td>
<td>32</td>
<td>0.22</td>
<td>1.09</td>
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<td>64</td>
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<td>50</td>
<td>2</td>
<td>1</td>
<td>64</td>
<td>.17</td>
<td>.88</td>
</tr>
<tr>
<td>10</td>
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<td>1</td>
<td>.5</td>
<td>32</td>
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<td>94.4</td>
</tr>
<tr>
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<td>.5</td>
<td>32</td>
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<td>48.6</td>
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<td>10</td>
<td>25</td>
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<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>.5</td>
<td>32</td>
<td>3.0</td>
<td>15.1</td>
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</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>
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<tbody>
<tr>
<td></td>
<td>R, r, mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>r, deg</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Line 1 (all radii the same #18 AWG)

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0.51</td>
<td>2.6393</td>
<td>0</td>
<td>+</td>
<td>Alt.</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>0.51</td>
<td>4.6593</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td></td>
<td>6.6793</td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td></td>
<td>8.6993</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td></td>
<td>10.7193</td>
<td></td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Line 2 (five different wire sizes)

<p>| | | | | | | |</p>
<table>
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<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0.3</td>
<td>2.6393</td>
<td>0</td>
<td>+</td>
<td>Alt.</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>0.51</td>
<td>4.6593</td>
<td>0</td>
<td>-</td>
<td>Alt.</td>
</tr>
<tr>
<td>3a</td>
<td>4</td>
<td>0.27</td>
<td>6.6793</td>
<td>0</td>
<td>+</td>
<td>Same</td>
</tr>
<tr>
<td>3b</td>
<td>8</td>
<td>0.45</td>
<td>22.5</td>
<td>45</td>
<td>+</td>
<td>Same</td>
</tr>
<tr>
<td>3c</td>
<td>4</td>
<td>0.51</td>
<td>8.6993</td>
<td>0</td>
<td>-</td>
<td>Same</td>
</tr>
<tr>
<td>4a</td>
<td>4</td>
<td>0.45</td>
<td>22.5</td>
<td>45</td>
<td>-</td>
<td>Same</td>
</tr>
<tr>
<td>4b</td>
<td>8</td>
<td>0.35</td>
<td>22.5</td>
<td></td>
<td>+</td>
<td>Same</td>
</tr>
<tr>
<td>4c</td>
<td>4</td>
<td>0.3</td>
<td>45</td>
<td></td>
<td>-</td>
<td>Same</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>0.51</td>
<td>10.7193</td>
<td>0</td>
<td>+</td>
<td>Alt.</td>
</tr>
</tbody>
</table>

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, Ω</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>
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<td>8.0</td>
<td>0.9</td>
<td>1.6</td>
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<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>0.349</td>
<td>57.0</td>
</tr>
<tr>
<td>22</td>
<td>65</td>
<td>0.244</td>
<td>0.245</td>
<td>0.349</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 $\varepsilon_r = 2.3$, $L = 10.42$ nH/m, $C = 2450$ pF/m, and $Z = 2.06$ Ω. Scale: 0.2 inch = 1 mm.
Table 1: Conditions and Inductance Values

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Line</th>
<th>( x_1 ) mm</th>
<th>( y_1 ) 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>1</td>
<td>2</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>Alt.</td>
</tr>
<tr>
<td>41 to 60</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>+</td>
<td>6</td>
<td>6</td>
<td>Alt.</td>
</tr>
<tr>
<td>61 to 80</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>-</td>
<td>8</td>
<td>8</td>
<td>Alt.</td>
</tr>
</tbody>
</table>

Figure 7. - 80-Wire (4x20) configuration with listing of individual self-inductances in nH/m ("Inductance" method). 

\[
L = 10.4196 \text{ nH/m; } C = 2.4526 \text{ nF/m; } Z = 2.0611 \Omega; A = 32.6851 \text{ mm}^2; r = 0.51 \text{ mm (#18 AWG).}
\]

Figure 8. - 80-Wire line ("Capacitance method") individual inductances. 

\[
L = 6.3115 \text{ nH/m; } C = 4.0490 \text{ nF/m; } Z_0 = 1.2685 \Omega; A = 32.68 \text{ mm}^2; r = 0.51 \text{ mm (#18 AWG).}
\]
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 Ω; A = 25.1327 mm²; r = 0.25 mm; εr = 2.3.
Figure 10. - Male-female junction boxes with conventional outlets.
(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.
**Title and Subtitle**
Transmission Line Design for a Power Distribution System at 20 kHz for Aircraft

**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 characteristics 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

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STAR Category 07