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SPACECRAFT CABLE MOD

SACAMOS: State of the Art CAble MOdels for Spice
Open Souce Cable Models for EMI Simulations

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Chapter 1

Introduction

The SACAMOS software [1] enables the creation of Spice cable models from the description/ characterisation of cables and bundles of cables together with information required to specify a particular modelling scenario (for example the specification of incident field excitation or transfer impedance coupling model).

Example models of cables used in spacecraft have been included with the software in a library of cable models referred to as 'MOD'. MOD also includes example Spice cable bundle models which make use of these cable models.

The cable models in the library are based on the ESCC specification documents (references [3] to [9]) and include twisted pair power lines, shielded twisted pair low frequency signal lines and RS422 cables plus SpaceWire cable assemblies, including connectors. This document describes the development of the library of cable models for spacecraft cables from these specifications and additional information where required i.e. how the information required in the cable specification **.cable_spec** file [2] is derived.

1.0.1 Cable types in MOD

The cable models defined in MOD are as follows:

1. Power lines: Twisted pairs with gauges 20, 22, 24, from 3 different standards [3], [4] and [5]
2. Low frequency signals: variant 12 Shielded Twisted Pair from the standard [5]
3. RS422 cables: variant 24 Shielded Twisted Pair from the standard [6]
4. SpaceWire: gauges 28 and 26 from the standard [7] and low mass SpaceWire cable from the stsndard [8]
5. Connectors for SpaceWire: 9 contact connector from the standard [9]

The cable naming convention combines the cable type (TP, STP, SPACEWIRE, LOW_MASS_SPACEWIRE) with the wire gauge (AWG 20, 22, 24, 26, 28), the ESCC specification document number and the particular cable variant number from within the specification.

The cable and connector models described here and made avaialble in MOD are as follows:

Twisted Pair models

`TP_AWG_20_ESCC_3901002_V34`

`TP_AWG_20_ESCC_3901019_V14`

`TP_AWG_20_ESCC_3901025_V10`

`TP_AWG_22_ESCC_3901002_V33`

`TP_AWG_22_ESCC_3901019_V13`

`TP_AWG_22_ESCC_3901025_V09`

`TP_AWG_24_ESCC_3901002_V32`

`TP_AWG_24_ESCC_3901019_V12`

`TP_AWG_24_ESCC_3901025_V08`

Shielded Twisted Pair models

`STP_AWG_26_ESCC_3901025_V12`

`STP_RS422_AWG_26_ESCC_3902002_V24`

SpaceWire Cable models

`SPACEWIRE_AWG_28_ESCC_3902003_V1`

`SPACEWIRE_AWG_26_ESCC_3902003_V2`

`LOW_MASS_SPACEWIRE_AWG_28_ESCC_3902004_V1`

`SPACEWIRE_CONNECTOR`

1.1 Dielectric materials

A number of different dielectrics are used in the construction of the cables specified. In all the cable models we assume that the dielectric material within each region is homogeneous, lossless and the relative permittivity is independent of frequency.

The relative permittivities used for the dielectrics used in spacecraft cable models are:

- polyimide: 3.4
- microporous PTFE: 1.3
- fluoropolymer PFA: 2.1

Chapter 2

Twisted Pair cable models

Twisted pair models have been developed with gauges 20, 22, 24, from 3 different standards [3], [4] and [5] i.e. 9 models in total.

The process followed to obtain the parameters for the **.cable_spec** file from information in the ESCC specifications is as follows (where we assume that all dimensions are converted to metres):

1. $$comnductor\_radius = \sqrt{\frac{nominal\_section}{\pi}} \tag{2.1}$$

2. $$dielectric\_radius = \frac{core\_max\_diameter}{2} \tag{2.2}$$

3. $$conductor\_separation = finished\_wire\_diameter - 2 * dielectric\_radius \tag{2.3}$$

4. The conductor in the model is a homogeneous cylindrical conductor so we need an effective conductivity. This is based on the maximum resistance (quoted in ohms/km)

$$Conductivity = \frac{length}{(max\_resistance * nominal\_section)} \tag{2.4}$$

5. The dielectric surrounding each conductor is also assumed to be homogeneous and independent of frequency.

   polyimide: $\epsilon_r = 3.4$

As an example, the cable specification for the 20AWG cable, variant 14 from [3]
TP_AWG_20_ESCC_3901019_V14.cable_spec:

```
#MOD_cable_lib_dir
LIBRARY_OF_CABLE_MODELS
Twisted_pair
2                 # number of conductors
4                 # number of parameters
   4.370E-04      # parameter 1: inner conductor radius
   1.520E-03      # parameter 2: inner conductor separation
   7.400E-04      # parameter 3: inner dielectric radius
   4.762E+07      # parameter 4: conductivity
1                 # number of frequency dependent parameters
# Dielectric relative permittivity model follows
1.0        # w normalisation constant
0   # a order, a coefficients follow below:
   3.400E+00
0   # b order, b coefficients follow below:
1.0
```

Chapter 3

Shielded Twisted Pair cable models

The shielded twisted pair models consist of variant 12 STP from the standard [5] for LF signals and RS422 cables: variant 24 STP from the standard [6].

The process followed to obtain the parameters for the **.cable_spec** from information in the ESCC specifications is as follows (where we assume that all dimensions are converted to metres):

1. $$comnductor\_radius = \sqrt{\frac{nominal\_section}{\pi}} \tag{3.1}$$

2. $$dielectric\_radius = \frac{core\_max\_diameter}{2} \tag{3.2}$$

   Note that the $core\_max\_diameter$ is not set in the ESCC 3902002 document [6]. In this case it is chosen such that the differential mode impedance of the shielded twisted pair model is the specified 120 ohms. For variant 12 STP from the standard [5] the dielectric diameter is chosen to be slightly less than the max core diameter from Table 1(a) so that th twisted pair fits inside the shield.

3. $$conductor\_separation = 2 * dielectric\_radius + \delta \tag{3.3}$$

   where δ is a small separtion distance, here assumed to be 0.01mm. This is required in order that the dielectric regions do no touch which would cause a problem for the mesh generation.

4. The conductor in the model is a homogeneous cylindrical conductor so we need an effective conductivity. This is based on the maximum resistance (quoted in ohms/km)

   $$Conductivity = \frac{length}{(max\_resistance * nominal\_section)} \tag{3.4}$$

5. $$shield\_radius = \frac{finished\_diameter}{2} - tj \tag{3.5}$$

   where tj is the outer jacket thickness. This is not specified in ESCC document but a typical value of 0.2mm is used

6. The shield thickness is set to zero. This indicates to the software that an 'equivalent thickness' should be calculated such that the d.c. resistance of the shield is consistent with the d.c. transfer impedance.

7. The dielectric surrounding each conductor is also assumed to be homogeneous and independent of frequency. Materials used in the STP cables are:

   Fluoropolymer: $\epsilon_r = 2.1$

   microporous PTFE $\epsilon_r = 1.3$

8. For RS422 cable, ESCC 3902/002 variant 24, the shield model is based on the shielding effectiveness curve in figure 1b. The usual definition of shielding effectiveness would make this a positive quantity however I am assuming that the curve here is of (1/SE)dB.

   If we assume that the shielding effectiveness can be related to the transfer impedance by the formula

   $$SE(dB) = 20log\left(\frac{2Z_0}{Z_T}\right) \tag{3.6}$$

   where Z_0 is the termination impedance in the transfer impedance measurement and Z_T is the transfer impedance, then

   $$Z_T = \frac{2Z_0}{10^{\frac{SE}{20}}} \tag{3.7}$$

   Here it is assumed that $Z_0 = 50\Omega$.

   A value of the shield d.c. resistance is derived from the SE as $f \rightarrow 0$.

9. For LF signal cable, variant 12 STP from the standard [5] no shielding effectiveness is specified so a 'reasonable' braid specification has been developed based on the requirement for 90% coverage and a shield strand diameter of 0.079mm. From this specification the theory of Kley [11] in appendix 1 is used to calculate a transfer impedance model of the form $Z_T = R_T + j\omega L_T$. In this case the braid specification is as follows:

```
1.4E-3          ! braid diameter, D (m)
8               ! Number of carriers, C
6               ! Number of wires in a carrier, N
0.079e-3        ! diameter of a single wire, d (m)
5E7             ! conductivity of wires (S/m)
52.0            ! pitch angle of the braid (degrees)
```

R_T is found as $\Re\{Z_T\}$ as $f \to 0$ and L_T is found as $\frac{\Im\{Z_T\}}{j\omega}$ at a suitably high frequency (1GHz here).

As an example, the cable specification for the 20AWG cable, variant 24 from [6] SPICE_MODEL_STP_RS422_AWG_26_ESCC_3902002_V24:

```
#MOD_cable_lib_dir
LIBRARY_OF_CABLE_MODELS
Shielded_twisted_pair
3                 # number of conductors
8                 # number of parameters
   2.111E-04      # parameter 1: inner conductor radius
   5.000E-04      # parameter 2: inner dielectric radius
   1.010E-03      # parameter 3: inner conductor separation
   1.050E-03      # parameter 4: shield radius
   0.000E+00      # parameter 5: shield thickness
   1.250E-03      # parameter 6:outer dielectric radius
   4.492E+07      # parameter 7: inner conductor conductivity
   4.492E+07      # parameter 8: shield conductivity
2                 # number of frequency dependent parameters
# Inner dielectric relative permittivity model follows
1.0        # w normalisation constant
0   # a order, a coefficients follow below:
   1.300E+00
0   # b order, b coefficients follow below:
1.0
# Shielded twisted pair outer dielectric relative permittivity model follows
1.0        # w normalisation constant
0   # a order, a coefficients follow below:
   2.100E+00
0   # b order, b coefficients follow below:
1.0
1                 # number of frequency dependent transfer impedance models
# Shielded twisted pair transfer impedance model follows
1.0        # w normalisation constant
1   # a order, a coefficients follow below:
   1.000E-01   5.035E-10
0   # b order, b coefficients follow below:
1.0
use_laplace
```

Chapter 4

SpaceWire cable models

The SpaceWire cable models, gauges 28 and 26 are derived from the standard [7] plus some additional information obtained from samples of cable for the shield transfer impedance specifications.

The low mass SpaceWire cable model is derived from the standard [8] plus some additional information obtained from samples of cable for the shield transfer impedance specifications.

The SpaceWire connector model is the 9 contact connector from the standard [9].

4.0.1 SpaceWire cable model

The SpaceWire cable model parameters have beed determined as follows:

1. $$comnductor\_radius = \sqrt{\frac{nominal\_section}{\pi}} \tag{4.1}$$

   DSC07340small.jpg

2. $$dielectric\_radius = \frac{core\_max\_diameter}{2} \tag{4.2}$$

3. The conductor in the model is homogeneous so we need an effective conductivity. This is based on the maximum resistance (ohms/km). Note this is a single conductor resistance.

   $$Conductivity = \frac{length}{(max\_resistance * nominal\_section)} \tag{4.3}$$

4. The dielectric is expanded microporous PTFE whose relative permittivity for the purpose of the calculation of the capacitance matrix for the shielded twisted pair is assumed to be 1.5. This is somewhat higher than the quoted value of 1.3 but the model does not include the dielectric filler or the binder materials so it artificially increased to try and compensate.

5. It is not possible now to use the dimensions in table 1a as these are maximum dimensions so I have an iterative process so as to obtain a viable twisted pair cross section with a differential mode impedance of 100 ohms. (Using the dimensions in table 1a gives an impedance of 140ohms).

   It is assumed that the distance between the insulation of the twisted pair is 0.01mm. This ensures that the dielectrics do not touch in the model which will cause the mesh generation to fail.

   The adjustable parameters are the inner dielectric radius, and the inner shield radius.

6. The inner conductor separation (here = 2*dielectric radius +0.01mm)

7. The inner shield jacket radius is the inner shield radius + the maximum inner jacket wall radius =0.2mm (section 4.4.7.2 from [7]). This and the outer jacket are made of extruded fluoropolymer PFA for which I am using a relative permittivity of 2.1.

8. The shielded twisted pair radius and the outer shield radius are chosen to give a sensible looking cable cross section while keeping within the maximum cable diameter (table 1a.)

9. The outer jacket thickness is 0.25mm (section 4.4.7.2 from [7])

10. Shield models.

    The shield conductivity is taken to be the same as for the inner wires and the shield thickness is set to zero in the **.cable_spec** file - this then allows the software to calculate an 'equivalent thickness' so that the d.c. resistance of the shield is equal to the d.c. transfer impedance.

    The shield transfer impedance models for the inner and outer shields cannot be based on the shielding effectiveness curve in figure 1b as this relates to the shielding effectiveness of the combination of inner and outer shields, connected together.

    The shield transfer impedance models are obtained by directly measuring the braid geometry of samples of both AWG28 and AWG26 SpaceWire cables and Low Mass SpaceWire cable. From photographs of both the inner and outer braids, the number of carriers, number of wires in a carrier and the pitch angle of the braid can be determined. From this specification the theory of Kley [11] in appendix 1 is used to calculate a transfer impedance model of the form $Z_T = R_T + j\omega L_T$.

    R_T is found as $\Re\{Z_T\}$ as $f \rightarrow 0$ and L_T is found as $\frac{\Im\{Z_T\}}{j\omega}$ at a suitably high frequency (1GHz here).

The shielding effectiveness of the SpaceWire models are shown in figures 4.1 and 4.2 respectively. These curves can be compared with figure 1b in the ESCC specification document.

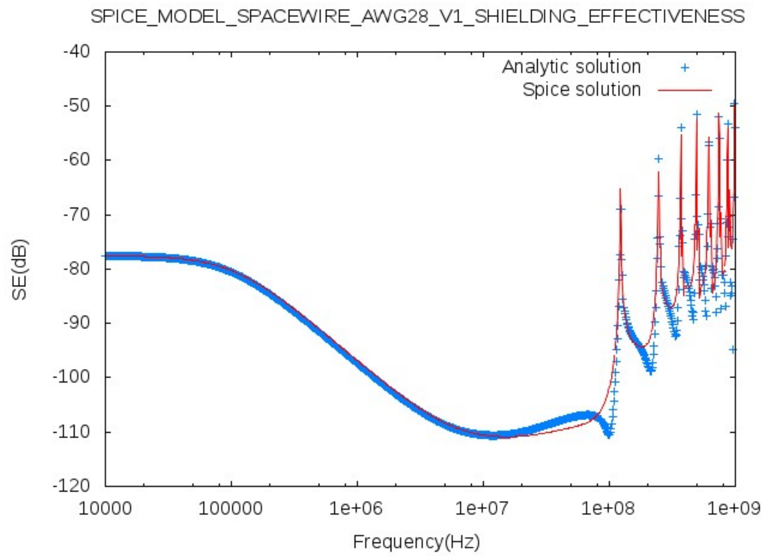

Figure 4.1 AWG 28 V1 SpaceWire Shielding Effectiveness

4.0.2 Low Mass SpaceWire cable model

The low mass SpaceWire cable model is derived in exactly the same way as the SpaceWire models. It should be noted that there is no insulation between the inner and outer shields of low mass SpaceWire although the model assumes that there is. This can lead to modes propagating in the model in the region between the inner and outer shields which will not exist in the real cable. This is illustrated in the shielding effectiveness calculation shown in figure 4.3 which shows the shielding effectiveness of 1m of the Low Mass spaceWire cable model. A model which is more representative of the real cable can be constructed by building the 1m cable from 10cm sections and connecting the inner shields and the outer shield together between each of the sections. The shielding effectivenes obtained from this model is shown in figure 4.4.

4.0.3 SpaceWire connector model

The SpaceWire connector model is specified as a Dconnector in the SACAMOS software. The parameters for the Dconnector model are obtained from the standard [9] as follows:

1. conductor_radius: fig 2.1 a,b
2. conductor_pitch (x_separation): fig 2.1 a,b
3. conductor y_separation: fig 2.1 a,b
4. offset from conductors to shell:fig 2.1 a,b; 0.5*(G-y_separation-2*conductor_radius)

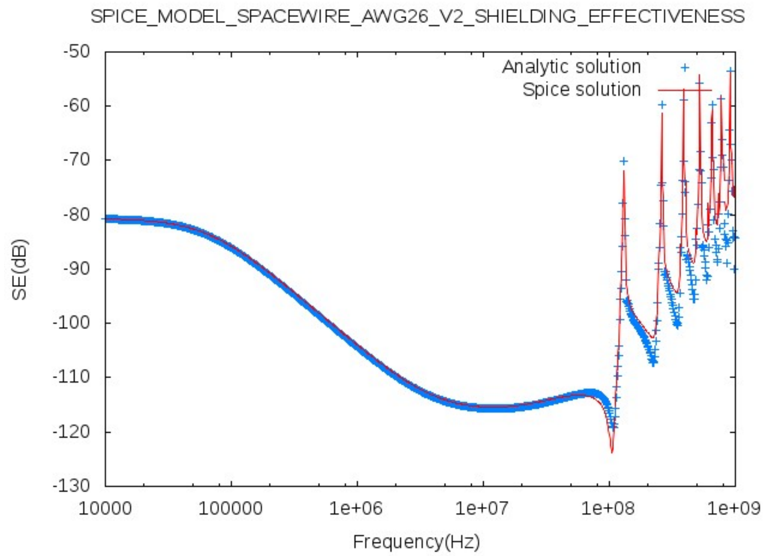

Figure 4.2 AWG 26 V2 SpaceWire Shielding Effectiveness

```
#MOD_cable_lib_dir
LIBRARY_OF_CABLE_MODELS
Dconnector
10 # number of conductors. This model from ESCC 3401/071, 9 pin connector
4 # number of parameters
0.43e-3   # parameter 1: conductor radius: fig 2.1 a,b
1.27e-3   # parameter 2: conductor pitch (separation in x): fig 2.1 a,b
1.09e-3   # parameter 3: conductor separation in y: fig 2.1 a,b
1.37e-3   # parameter 4: offset from conductors to shell:fig 2.1 a,b;
                              0.5*(G-yseparation-2*rw)
0 # number of frequency dependent parameters
0 # number of transfer impedance models
use_laplace
```

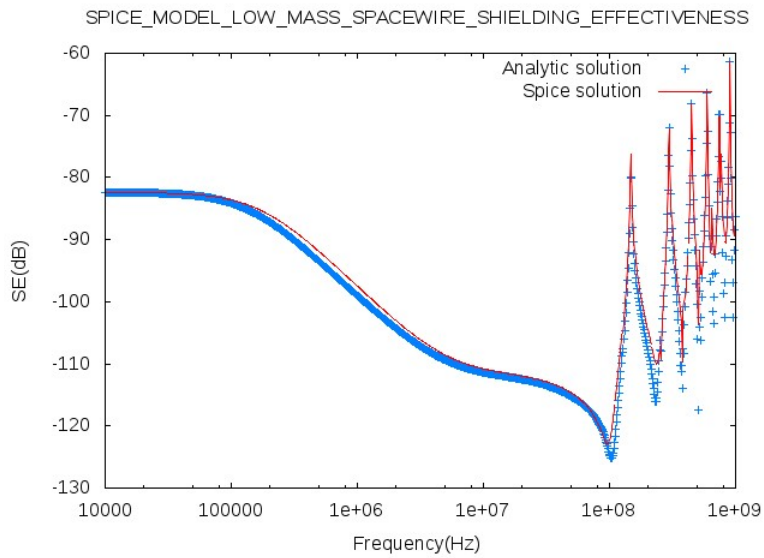

Figure 4.3   Low Mass Spacewire shielding effectiveness

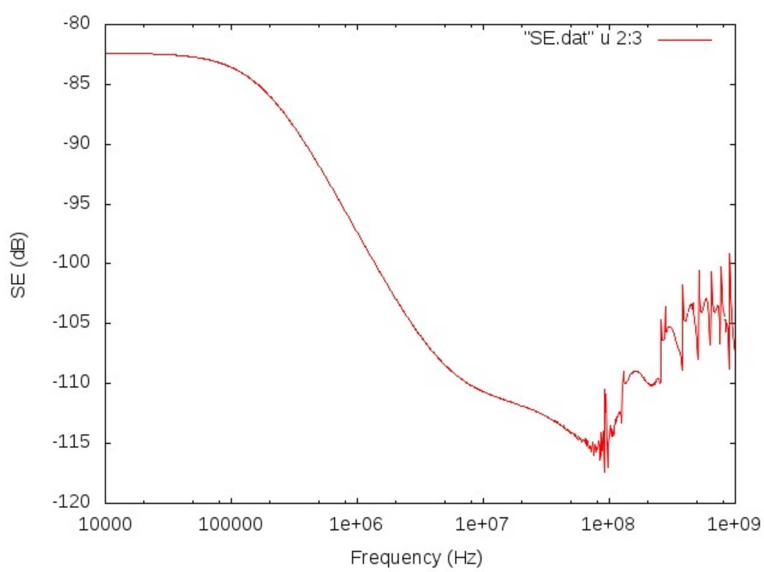

Figure 4.4   Low Mass Spacewire shielding effectiveness which shields connected every 10cm

Bibliography

[1] www.sacamos.org

[2] C. Smartt, D.W.P. Thomas, S. Greedy, J. Verpoorte, J. Lansink Rotgerink *SACAMOS User Guide*

[3] *ESCC 3901/019: POLYIMIDE INSULATED WIRES AND CABLES, LOW FREQUENCY, 600V, -200 TO +200C BASED ON TYPE SPL* https://escies.org/download/specdraftapppub?id=2686

[4] *ESCC 3901/002: POLYIMIDE INSULATED WIRES AND CABLES, LOW FREQUENCY, 600V, -100 TO +200C* ESCC Detail Specification No. 3901/002 https://escies.org/download/specdraftapppub?id=2558

[5] *ESCC 3901/025: LIGHTWEIGHT, EXTRA THIN, FLUORTHERMOPLASTIC / POLYIMIDE INSULATED WIRES AND CABLES, LOW FREQUENCY, 600V, -200 TO +200 C BASED ON TYPE CSC* https://escies.org/download/specdraftapppub?id=2557

[6] *ESCC 3902/002: COAXIAL, TRIAXIAL AND SYMMETRIC CABLES, FLEXIBLE, -200 TO +180 oC* https://escies.org/download/specdraftapppub?id=2986 Cable:

[7] *ESCC 3902/003: CABLE, 'SPACEWIRE', ROUND, QUAD USING SYMMETRIC CABLES, FLEXIBLE, -200 TO +180C* https://escies.org/download/specdraftapppub?id=3125

[8] *ESCC 3902/004: CABLE, LOW MASS, 'SPACEWIRE', ROUND, QUAD USING SYMMETRIC CABLES, FLEXIBLE, -100 TO +150C*

[9] *ESCC 3401/071: CONNECTOR, ELECTRICAL, RECTANGULAR, MICROMINIATURE, SOLDER BUCKET CONTACTS, WITH EMI BACKSHELL BASED ON TYPE MDM* https://escies.org/download/specdraftapppub?id=2702

[10] E. F. Vance *Shielding effectiveness of braided wire shields*, IEEE transactions on EMC, vol EMC-17, no 2, 1975, pp71-77

[11] T. Kley *Optimized single-braided cable shields* IEEE Transactions on Electromagnetic Compatibility, vol.35, no.1, pp.1,9, Feb 1993

[12] F. M. Tesche, M. V. Ianov, T. Karlsson, *EMC Analysis Methods and Computational Models* John Wiley and Sons, 1997.

Appendix A

Transfer Impedance model according to Kley

From the work of Vance [10] and Kley [11] and the summary of this work in [12] we may calculate the frequency dependent transfer impedance of a braided wire shield from the cable shield parameters. The shield parameters are

1. braid diameter, D
2. Number of carriers, C
3. Number of wires in a carrier, N
4. diameter of a single wire, d
5. conductivity of wires, σ
6. pitch angle of the braid, α

These parameters are illustrated in figure A.1.

The transfer impedance is the sum of the effects of diffusion through the shield conductor, penetration of the field through the holes in the shield and the effects of the overalpping weave of the braid conductors.

$$Z_t = Z_d + j\omega M_h + j\omega M_b \tag{A.1}$$

The calculation of the transfer impedance terms proceeds as follows:

The fill factor, F, is calculated as

$$F = \frac{NCd}{2\pi Dcos(\alpha)} \tag{A.2}$$

The optical coverage, K, is

$$K = 2F - F^2 \tag{A.3}$$

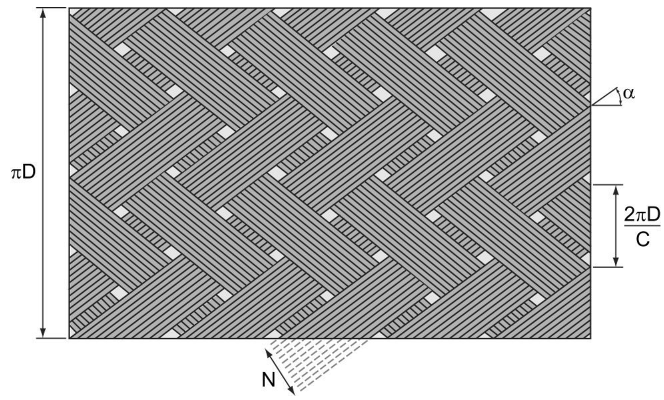

Figure A.1 Braid parameters

The length and width of the rhombic holes are given by

$$l = \frac{(1-F)\,Nd}{Fsin(\alpha)} \tag{A.4}$$

$$w = \frac{(1-F)\,Nd}{Fcos(\alpha)} \tag{A.5}$$

a parameter, e, is defined as

$$e = \sqrt{1 - \left(\frac{w}{l}\right)^2} \tag{A.6}$$

The diffusion impedance term is given by

$$Z_d = R_0 \frac{\gamma}{sinh(\gamma t)} \tag{A.7}$$

where R_0 is the d.c. resistance of the shield

$$R_0 = \frac{4}{\pi d^2 NC\sigma cos(\alpha)} \tag{A.8}$$

γ is the propgation constant in the shield conductor

$$\gamma = \frac{1+j}{\delta} \tag{A.9}$$

where

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma}} \tag{A.10}$$

and t is an equivalent thickness of the cable shield given by

$$t = \frac{1}{\pi\sigma D R_0} \tag{A.11}$$

The hole inductance term is given by

$$M_h = \frac{\mu_0 \pi (1-K)^{\frac{3}{2}}) e^2}{6C(Em(e) - (1-e^2)Km(e))} * C_k \tag{A.12}$$

where Km and Em are elliptic integrals and

$$C_k = 0.875 e^{-T_h} \tag{A.13}$$

$$T_h = 9.6F \left(\frac{K^2 d}{2a} \right)^{\frac{1}{3}} \tag{A.14}$$

$$a = D/2d0 + d \tag{A.15}$$

$$M_b = \frac{-0.22\mu_0 d}{4\pi D_m F cos(\alpha)} cos(2k_1\alpha) \tag{A.16}$$

where

$$k_1 = \frac{\pi}{2.667F cos(\alpha) + \frac{\pi}{10}} \tag{A.17}$$

and

$$D_m = D + 2d \tag{A.18}$$