

# Advanced models for the transfer impedance of metal braids in cable harnesses

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**Abstract**— Since the development of the model for transfer impedance of metal braids by E.F. Vance, a large number of authors have tried to improve this model in order to make it more accurate and more reliable. The improvements were based on a more accurate physical or electromagnetic description, or on empirical data of a large number of transfer impedance measurements. This paper provides an overview of the specific models for diffusion, hole inductance and braid inductance. In addition to the general overview, a preferred combination of models for the calculation of transfer impedance is presented.

**Keywords**— Cable shielding, Electromagnetic compatibility, transfer impedance, shielding effectiveness

## I. INTRODUCTION

In order to prevent Electromagnetic Interference (EMI), cables between equipment are often shielded. The shielding effectiveness of these cable shields is an important parameter in coupling between cables (crosstalk) and pick-up of interference from electromagnetic fields. These cable shields can be made of solid or flexible material. Solid metal shields are not often used because they are heavy and more difficult to install. However, they do offer a very good shielding effectiveness. Flexible shields consist mostly of metal braids (Fig. 1), but can also be made of layers of conducting tape. For all these types of shields, the shielding effectiveness can be determined by calculation or measurement. The shielding effectiveness is often expressed in terms of the transfer impedance of the shield. The transfer impedance relates the shield current (caused by an external source) to the longitudinal voltage drop inside the shield. This internal voltage will manifest itself as a common mode voltage for the wire or wires inside the shield. The transfer impedance is defined by:

$$Z_t = \frac{1}{I} \frac{\partial V}{\partial z}, \quad (1)$$

with  $I$  the total current in the shield and  $V$  the longitudinal voltage difference over an infinitesimal small section of the shield ( $z$  is the longitudinal direction).

The transfer impedance is a property of the shield alone and therefore independent of the conductors inside the shield, as well as the external circuit of which the shielded cable is part.

The transfer impedance of a metal braid is related to the coupling produced by penetration of the magnetic field

through the openings in the shield. There may also be electric coupling produced by an electric field penetrating through the holes in the shield and terminating on the inner conductors. This transfer admittance is the susceptance per unit length between the inner conductors and the shield and the return-current path of the shield. To analyze the transfer admittance, also the external circuit of the shielded cable should be taken into account. This paper will address the transfer impedance only. The transfer impedance model can be subdivided into different phenomena, such as diffusion, hole inductance, braid inductance and skin inductance. Since the development of the model for transfer impedance of metal braids by E.F. Vance [6], a large number of authors have tried to improve the different parts of this model to make it more accurate and more reliable. Among them are Tiny [7], Sali [10], Kley [9], Katakis [8], Wang [16] and Schippers [17][18]. In the next sections the characteristics and limitations of the various available models for diffusion, as well as braid, hole and skin inductance will be addressed.

For the determination of braid inductance a new calculation method is presented in section III.C, which is an improvement of Tiny's model [7]. Furthermore, in section IV recommendations are given for the calculation of the hole and braid inductances of the transfer impedance model.

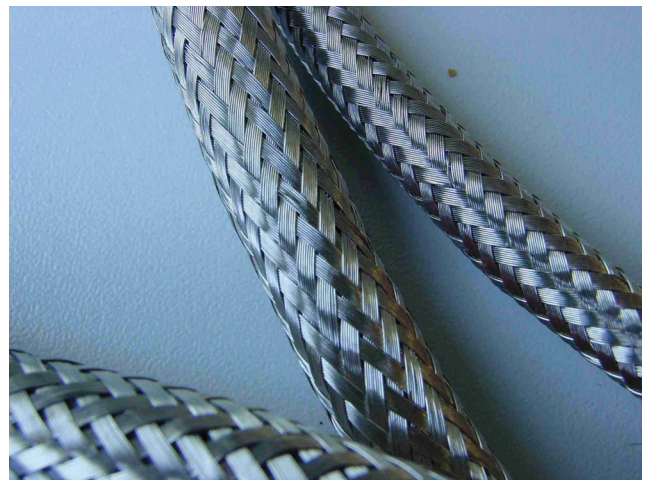


Fig. 1. Cable shields consisting of metal braids.

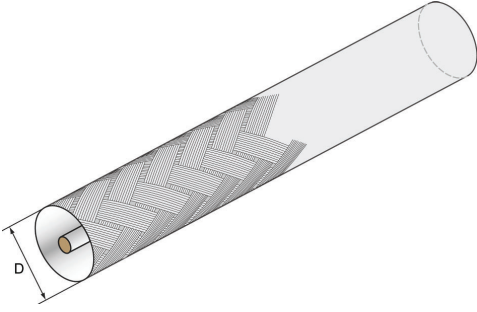


Fig. 2. Metal braid for cable (diameter of braid is D).

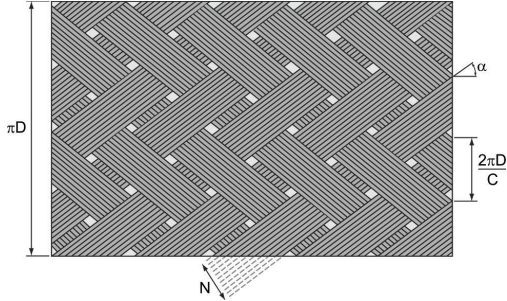


Fig. 3. Characteristics of metal braid.

## II. GENERAL MODEL FOR TRANSFER IMPEDANCE

All existing analytical models of transfer impedance of metal braids use the braid parameters as input (see Fig. 2 and Fig. 3). These parameters are:

- Diameter  $D$  of braid.
- Number of carriers  $C$  (i.e. belts of wires) in the braid (integer number).
- Number of wires  $N$  in a carrier (integer number)
- Diameter  $d$  of a single wire.
- Conductivity  $\sigma$  of the wires.
- Weave angle  $\alpha$  of the braid.

Depending on the value of these parameters, the values and behaviour of the transfer impedance changes. The general model for calculation of the transfer impedance contains two components: one part ( $Z_d$ ) representing diffusion of electromagnetic energy through the metal braid, and a second part ( $j\omega M$ ) representing leakage of magnetic fields through the braid:

$$Z_t = Z_d + j\omega v M. \quad (2)$$

Here  $v$  is the number of holes per unit length. The diffusion component  $Z_d$  of the metal braid is governed by the DC resistance of the metal braid and by diffusion of waves through the wall of the cylindrical braid. Vance and Kley have proposed models for the diffusion.

The inductance  $M$  in (2) is the superposition of the hole inductance  $M_h$ , braid inductance  $M_b$  and skin inductance  $M_s$ :

$$M = M_h + M_b + M_s. \quad (3)$$

Authors like Vance, Kley and Schippers have derived models for these inductance terms as part of the transfer impedance.

The contributions to the total inductance will be explained in more detail in the next sections.

## III. SPECIFIC MODELS FOR (PARTS OF) THE TRANSFER IMPEDANCE

### A. Diffusion through the shield

#### 1) Vance

Vance [5], [6] was one of the first authors to derive an analytical model for the transfer impedance of metal braids. He provided a model for the diffusion component and for the hole inductance. The diffusion component  $Z_d$  of the metal braid is related to the DC resistance of the metal braid and to the diffusion of waves through the wall of the cylindrical braid. Vance proposed to model  $Z_d$  as:

$$Z_d = R_0 \frac{\gamma d}{\sinh \gamma d}, \quad (4)$$

where  $d$  is the thickness of the wires in the metal braid, and  $\gamma$  is the complex propagation constant of the wires ( $\gamma = (1 + j)/\delta$ , with  $\delta$  the skin depth of the wire,  $\delta = \sqrt{2/\omega\mu\sigma}$ ). The DC resistance  $R_0$  is governed by the conductivity  $\sigma$  and the averaged cross section of the braid. It is computed per unit length and equals:

$$R_0 = \frac{4}{\pi d^2 N C \sigma \cos(\alpha)}. \quad (5)$$

#### 2) Kley

Based on measurements on practical cables with single metal braids, Kley [9] proposed an improvement for the diffusion component  $Z_d$  of the transfer impedance:

$$Z_d = R_0 \frac{\gamma d'}{\sinh \gamma d'}, \quad (6)$$

where  $d'$  is the approximate thickness of the wires in the metal braid:

$$d' = 0.67d / \sqrt{\cos \alpha}. \quad (7)$$

For practical values of  $d$  and  $\alpha$ , the values predicted by Kley are somewhat higher than those predicted by Vance.

### B. Hole Inductance

The first term of (3) is related to the inductance of magnetic fields through the apertures in the metal braid. The inductance is a local phenomenon. Expressions for the inductance can be derived by considering the inductance through a single aperture and then superimposing the contributions of all apertures. Hence, the interaction of induced magnetic fields through neighboring apertures is usually neglected.

#### 1) Kaden

Kaden, in his book about eddy currents and shielding of transmission lines [1], was the first to address the coupling of electric and magnetic fields through holes in metal shields. For the calculation of transfer impedance of braided shields,

especially the coupling of magnetic fields through apertures in the shield is important. Kaden showed the influence of the size of the hole on the coupling, but also the influence of the depth of the hole (thickness of the shield) on the coupling. However, he only addressed the influence of *circular* holes.

Kaden showed that the magnetic polarizability  $m$  of *circular* holes with radius  $r$  (in a zero-thickness wall) is given by:

$$m = 8r^3 / 3. \quad (8)$$

The polarizability of a hole is the ratio of the effective dipole moment of the magnetic field penetrating the hole to the undisturbed magnetic field at the surface. The magnetic polarizability can also be written as function of  $S$ , the surface area of the hole:

$$m = \frac{8}{3\pi\sqrt{\pi}} S^{3/2}. \quad (9)$$

#### 2) Vance

Vance [5] proposed to calculate the hole inductance  $M$  by:

$$M = M_h = \frac{\mu m}{2\pi^2 D_m^2}. \quad (10)$$

In his analysis of a perforated solid shield Vance also shows that the magnetic coupling not only depends on the transparency of the shield, but also on the size of the apertures. Thus a shield with a given transparency will cause more coupling if the transparency is due to a few large holes, than if this is due to many small holes.

The hole inductance (as part of the transfer impedance) is related to the penetration of magnetic fields through holes in the shields. It is clear that the shape of these holes is always of a rhombic type (Fig. 3). The hole inductance increases linearly by the value of the magnetic polarizability  $m$  of a rhombic hole. In the models of Vance [5] this polarizability is approximated by the polarizability of an equivalent elliptical hole, while the apertures in the metal braid are rhombic. Vance only addresses hole inductance and neglects braid inductance and skin inductance. Expressions for the magnetic polarizability for elliptical holes are presented in section 4 of this chapter.

#### 3) Kley

Kley [9] derived empirical models for the transfer impedance from measurements on many different single shielded cables. Kley proposed an improved model for the hole inductance and empirical models for braid inductance and skin inductance. The hole inductance of Kley reads:

$$M_h = 0.875 \frac{\mu m}{2\pi^2 D_m^2} e^{-\tau}. \quad (11)$$

The factor 0.875 in (11) takes into account the curvature of the braid. The outer diameter  $D_m$  of the braid is approximated by:

$$D_m = D_0 + 2d, \quad (12)$$

with  $D_0$  the diameter under the braid.

The effect of the wall thickness of the braid is taken into account by multiplying the hole inductance as defined by Vance (10) with an attenuation factor  $\exp(-\tau)$  due to the so-called ‘‘chimney’’ effect. This factor  $\tau$  in the exponential of (11) equals:

$$\tau = 9.6F \sqrt[3]{F^2(2-F)^2 d / D_m}, \quad (13)$$

where  $F$  is the fill of the braid:

$$F = \frac{NCd}{2\pi D_m \cos \alpha}. \quad (14)$$

This ‘‘chimney’’ effect can reduce the magnitude of the hole inductance significantly.

#### 4) De Smedt

Analytical formulas for the magnetic polarizability of elliptical apertures are already known for a long period (see [13]). The expressions in this section are from [4]. Let  $e$  be the eccentricity of the ellipse,  $e = \sqrt{1 - (w/l)^2}$  (with  $l$  the major axis and  $w$  the minor axis). For weave angles  $\alpha$  larger than 45 degrees the magnetic fields (due to a current along the axis) are parallel to the major axis. For this case, the magnetic polarizability equals [4]:

$$m_l = S^{3/2} v_{mx}, \quad (15)$$

with:

$$v_{mx} = \frac{2}{3\sqrt{\pi}} \left(\frac{l}{w}\right)^{3/2} \left(\frac{e^2}{K(e) - E(e)}\right). \quad (16)$$

For weave angles  $\alpha$  less than 45 degrees the magnetic fields (due to a current along the axis) are parallel to the minor axis of the rhombic aperture. For this case, the magnetic polarizability is:

$$m_w = S^{3/2} v_{my}, \quad (17)$$

with:

$$v_{my} = \frac{2}{3\sqrt{\pi}} \left(\frac{l}{w}\right)^{3/2} \left(\frac{(1-e^2)e^2}{E(e) - (1-e^2)K(e)}\right). \quad (18)$$

In the above equations  $K(e)$  and  $E(e)$  are the complete elliptical integrals of the first and second kind. The quantities  $v_{mx}$  and  $v_{my}$  are dimensionless and are referred to as the normalized magnetic polarizabilities.

For four typical apertures the magnetic polarizability has been computed by De Smedt [3] and De Meulaere [4] using numerical techniques. They have shown that the dimensionless magnetic polarizability for ellipses, rectangles with and without rounded ends and rhombic holes shows similar behavior for a range of aspect ratios. For aspect ratios equal to one ( $w = l$ ) the difference is only 8 % (see Fig. 5 in [3]).

### 5) Schippers

Schippers [15], [16] has shown that the magnetic polarizability in the hole inductance models of Vance and Kley is overestimated. In these models, the area of the rhombic aperture is approximated by the surface of an elliptical hole:

$$S_e = \pi lw / 4, \quad (19)$$

with  $l$  the major axis and  $w$  the minor axis of the ellipse. However, the correct surface of the rhombic aperture reads:

$$S_r = lw / 2. \quad (20)$$

This value of the rhombic aperture should be used in (15) and (17), and not the surface area of an elliptical aperture. Hence, from (15) and (17), the factor of overestimation amounts to:

$$\Gamma = (S_r / S_e)^{3/2} = (2 / \pi)^{3/2} = 0.5079. \quad (21)$$

Hence, the hole inductance equations in Vance and Kley should be reduced by a factor  $\Gamma = 0.5079$ .

### C. Braid Inductance

The braid inductance is due to generation of a magnetic field in the space between the carriers due to a current  $I$  that flows in the wire of the carrier, locally on the inner side (see Fig. 4). The magnetic field due to this current is given by:

$$\vec{H} = \hat{s} I / (NCd), \quad (22)$$

with  $N$  the number of wires in a carrier,  $C$  the total number of carriers in the braid, and  $d$  the diameter of the wires. The magnetic flux  $\Phi$  through the space at the cross over is:

$$\Phi = -\mu \vec{H} \cdot \hat{n} S, \quad (23)$$

with  $\hat{n}$  the local normal (see Fig. 4) of the area and  $S$  the marked area between the carriers, as indicated in Fig. 5. The local normal  $\hat{n}$  is given by  $\hat{n} = \cos(2\alpha)\hat{s} - \sin(2\alpha)\hat{t}$ . As a consequence, the local flux due to the space between the carriers becomes:

$$\Phi = -\mu \frac{I}{NCd} \cos(2\alpha) S. \quad (24)$$

The magnetic braid inductance through area  $S$  follows from  $M_{b,S} = \Phi / I$ . The total braid inductance  $M_b$  follows from multiplying  $M_{b,S}$  by the number of picks  $P$  per unit length. From [6] it follows that  $P$  is given by:

$$P = C \tan \alpha / 2\pi D_m. \quad (25)$$

Then, the total braid inductance becomes:

$$M_b = -\mu \frac{S}{Nd} \frac{\tan \alpha}{2\pi D_m} \cos(2\alpha), \quad (26)$$

which can be reformulated as:

$$M_b = -\mu \frac{S}{Nd} \frac{(1 - \tan^2 \alpha)}{4\pi D_m} \sin(2\alpha). \quad (27)$$

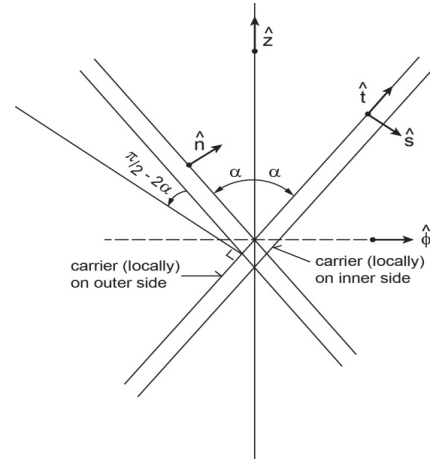


Fig. 4. Local coordinate system for carriers in a braid.

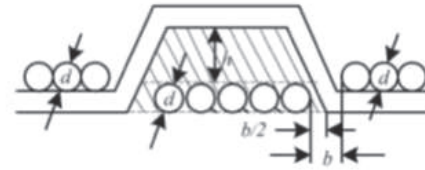


Fig. 5. Area between inner and outer braid layers at the crossover.

#### 1) Tiny

A first approximation of the surface  $S$  of the crossover (see Fig. 5) is  $S = Ndh$ , with  $h$  the average height between the carriers. Furthermore, for braids with a weave angle close to 45 degrees  $\sin 2\alpha \approx 1$ . Then, the braid inductance in (27) can be approximated by:

$$M_b = -\mu h \frac{(1 - \tan^2 \alpha)}{4\pi D_m}, \quad (28)$$

which is applied by Tyni [7] for all weave angles less than 45 degrees. It remains to specify an approximation for the height  $h$ . Tyni uses the following formula:

$$h = \frac{2d}{1 + b/d}, \quad (29)$$

with  $b$  the width of the split between two carriers (see Fig. 5) given by  $b = (2\pi D_m / C) \cos \alpha - Nd$ .

#### 2) Katakis

A modification of Tiny's braid model was discussed by Benson [12], where a reference has been given to the Master's thesis of Katakis [8]. It has been argued that the outer diameter  $D_m$  of the braid must also depend on the height between the strands, thus:

$$D_m = D_0 + 2d + h. \quad (30)$$

Then, for a fixed laylength  $L$  of the braid the weave angle becomes:

$$\tan \alpha = \pi(D_0 + 2d + h) / L. \quad (31)$$

Furthermore, the following equation holds:

$$\left(\frac{2\pi}{C} \cos \alpha\right) h^2 + \left((1-N)d + \frac{2\pi}{C} D_i \cos \alpha\right) h - 2d^2 = 0. \quad (32)$$

with  $D_i = D_0 + 2d$ .

The solution of the non-linear system of equations (31)-(32) provides a new approximation for the weave angle  $\alpha$  and the average height  $h$ , which is then used in equation (30) to obtain the outer diameter, and then subsequently applied in formula (28) to obtain a value for the braid inductance. A similar non-linear system for the determination of angle  $\alpha$  and  $h$  was presented by Sali in [10], who also proposed an improved expression for the braid inductance which approaches equation (27). In [10] the area  $S$  between the carriers is obtained by means of complicated expressions.

### 3) Wang Xiaoling

Another improvement for modelling braid inductance has been proposed by Wang in [16], who calculates  $M_b$  as follows:

$$M_b = -\frac{\mu SA}{2\pi CD_m \cos \alpha}, \quad (33)$$

with  $A = (\sqrt{v} + 1)^2 \cos 2\alpha$ . The number of holes  $v$  per unit length is in general large. Then,  $A$  can be approximated by  $v \cos 2\alpha$ . From Vance [6] it follows that  $v = PC$ . Then,  $A$  becomes:

$$A = \frac{C^2}{4\pi D_m} \sin 2\alpha (1 - \tan^2 \alpha). \quad (34)$$

Substitute (34) into to(33) obtain:

$$M_b = -\frac{\mu S}{4\pi N d D_m} (1 - \tan^2 \alpha) F \sin 2\alpha, \quad (35)$$

with  $F$  the fill factor of the braid. For many braids the fill factor is close to one. Then, (35) reduces to (27). In [16] the area  $S$  between the carriers is approximated by:

$$S = Ndh + bd \left(1 - h^2 / d^2\right) / 2 + Nd^2(1 - \pi / 4). \quad (36)$$

with  $b$  once again the width of the split between two carriers. The average height follows from the simultaneous solution of (31) and:

$$\left((1-N)d + \frac{2\pi}{C} (D_0 + 2d) \cos \alpha\right) h - 2d^2 = 0. \quad (37)$$

Observe that this equation is a simplification of expression (32) since the first term in that equation has been neglected.

### 4) Kley

For the braid inductance, Kley [9] applies the following approximate equation:

$$M_b = -\mu \frac{d}{4\pi D_m} \frac{0.22}{F \cos \alpha} \cos(2k_1 \alpha), \quad (38)$$

where:

$$k_1 = \pi / 4 \left[ \frac{2}{2} F \cos \alpha + \frac{\pi}{10} \right]^{-1}.$$

The main difference between the braid inductance of Tiny and Kley is the dependence on the weave angle  $\alpha$ . By (28) Tiny supposes that the braid inductance decreases by:

$$m_T^\alpha = 1 - \tan^2 \alpha, \quad (39)$$

for increasing weave angles, while Kley assumes a decrease by a factor:

$$m_K^\alpha = \frac{0.22}{F \cos \alpha} \cos(2k_1 \alpha). \quad (40)$$

For weave angles less than 45 degrees, Kley's empirical model according to (38) reduces the effect of the braid inductance much more than Tiny's approximated model given by (28).

Interesting to note is that for weave angles  $\alpha < 45^\circ$  the hole inductance and braid inductance have an opposite sign. This implies that if the braid inductance is dominant over the hole inductance, the transfer impedance will change polarity.

### 5) Summary braid inductance models

In the present paper we have derived (27) for the calculation of braid inductance. The frequently used formula of Tyni [7], see (28), can be considered as first approximation of (27). Also the formulas as presented in [10] and [16] are similar to (27). Only formula (38) of Kley [9] yields a smaller contribution to braid inductance for weave angles less than 45 degrees.

Notice that the present formula (27) contains still the determination of the area  $S$  between the carriers. The most accurate formula available so far is given by (36), which is dependent on the average height between the carriers. Expressions for the determination of the average height have been presented in references [7], [10], [12], [16]. It is our experience that reasonable accurate results can be already obtained by Tyni's expression (29). In [18] we have addressed the large uncertainties in the calculation of the braid inductance due to the sensitivity of the average height between the carriers of the braid.

## D. Skin Inductance

### 1) Kley

In the semi-empirical models as described by Kley [9], also a third inductance term is introduced, the skin inductance  $M_s$ , which is due to eddy current in the walls of the rhombic apertures. The skin inductance is given by

$$M_s = \frac{(1-i)}{\omega \pi \sigma \delta D_m} [10\pi F^2 \cos \alpha (1-F) e^{-\tau_E} - \frac{3.3}{2\pi F \cos \alpha} \cos(2k_2 \alpha)] \quad (41)$$

where  $k_2 = (\pi / 4) / ((2/3) * F + (3/8))$  and

$\tau_E = 12G \sqrt[3]{B^2 d / D_m}$ . See Ref. [9] for more details.

If this skin inductance is taken into account, the inductance  $M$  in (2) is the superposition of the hole inductance, braid inductance and skin inductance (3). However, the skin inductance  $M_s$  is negligible in comparison to the contributions of hole and braid inductance for high frequencies, since for  $\omega \rightarrow \infty$   $M_s$  appears to be of  $O(\omega^{-1/2})$  while the other terms are of  $O(1)$ .

#### IV. PREFERRED COMBINATION OF MODELS FOR TRANSFER IMPEDANCE

For the calculation of the diffusion through the shield we recommend the application of (6) and (7). For the calculation of hole inductance we recommend to use the following:

$$M_b^S = 1.08\Gamma M_b, \quad (42)$$

where  $M_b$  is given by Kley's expression (11). The correction factor 1.08 is due to the 8 % difference between the values for dimensionless magnetic polarizability of elliptical and rhombic apertures (see [17]) for aspect ratio one. The correction factor  $\Gamma$  has been explained in (21).

In the present paper we have proposed to calculate the braid inductance by formula (27) and the area  $S$  between the carriers by (36). The average height in (36) can be determined by Tyni's expression (29).

Finally, the contribution of skin inductance can be calculated by the empirical formulas presented by Kley [9].

#### V. TERMINATION OF THE SHIELD

It should be noted that the termination of the shield may have a significant influence on the transfer impedance of an installed shielded cable. If the termination of the shield is not around the full  $360^\circ$  on the connector, but with a single wire (pigtail), then the shielding effectiveness will be degraded. Moreover, if the shield has a poor (resistive) bonding to the connector, this will decrease the shielding. The finishing of the shield can be modelled as a separate transmission line cascaded with the shielded transmission line. As a simple approximation, the properties of the finishing can be added to the transfer impedance of the shielded cable. Suppose we have a cable RG-58. The transfer impedance of such a cable is approximately [19]:

$$Z_t = 0.01 + j\omega 0.5 \cdot 10^{-9} \Omega / m \quad (43)$$

Suppose that to 1 m or this cable a pigtail of 1 cm is applied. Then an inductance of approximately 10 nH (rule of thumb of 1  $\mu\text{H}/\text{m}$  inductance for a wire pair) is added to the 0.5 nH inductance of 1 m RG-58. Moreover, if poor bonding is applied, e.g. in the order of 10 m $\Omega$ , this will be added to the existing 10 m $\Omega$  of the 1 m shield. This shows that proper termination of shield is very important in order to maintain sufficient shielding effectiveness.

#### VI. CONCLUSION

In this paper, we have described multiple models for improvement of the general transfer impedance model derived by Vance. Some models are based on an analytical approach,

others on an empirical approach. It should be mentioned that also numerical models exist [14], but those have not been discussed here. For each model mentioned in this paper we have discussed the applicability and the limitations. Finally, we have indicated a preferred combination of (parts of) those models for the diffusion impedance, the hole inductance, the braid inductance and the skin inductance. The information in this paper will enable the reader to select the right models when calculating the transfer impedance of a specific metal braid.

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