Shielding Effectiveness of HSD Connector – Simulation and Measurement

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Abstract ─ The goal of designing a shielded High-Speed Data (HSD) connectors is to find the ideal balance between economy and performance. The connectors are a part of many systems and they influence their performance. The connectors should be designed to avoid possible negative effects on system properties. Thus, it is necessary to analyze the shielding effectiveness of connectors to ensure the electromagnetic compatibility (EMC) of the whole system. The transfer impedance is an effective shield parameter used to evaluate the shielding effectiveness of cables and connectors. Based on the analysis of the limitation of available test methods, a 3D model is developed to numerically calculate the transfer impedance of the HSD connector. Even though numerical methods were used, the theoretical foundations necessary to interpret the obtained results are revisited. The theory associated with cable shielding is revisited through solving known equations for the transfer impedance of a coaxial cable with a braided shield and foil.

Index Terms ─ electromagnetic compatibility, shielding effectiveness, transfer impedance.

I. INTRODUCTION

The concept of transfer impedance introduced by Schelkunoff [1] is used to measure the shielding effectiveness of cable shields [2, 3]. Transfer impedance is the property of the shield that relates the voltage induced in the shielded circuit to the current in the shield. To consider the employment of transfer impedance for practical purposes, it should be easily evaluated and measured. There are many developed measurement techniques, standardized tests, guides and descriptions in the literature that give good analytical and empirical approaches for determining transfer impedance of common geometries such as the tubular and braided shield. According to the evaluations in the literature, the transfer impedance at low and medium frequency range can be accurately determined. Transfer impedance Z_T is equal to the DC resistance of the shield up to the frequency where the ratio of the thickness of the shield and skin depth is much less than 1, i.e., $\Delta\backslash\delta \ll 1$ [4]. The developed analytical expressions for calculation of transfer impedance for higher frequency range, where inductance plays an important role, are lacking accuracy [5].

The known approaches for calculating the transfer impedance for a complex geometry such as the braided shield are primarily based on semi-empirical models where analytical formulations are modified based on the experimental results obtained by measuring many various braids [6]. The Semi-empirical models compare well against the measured values for a limited number of braids where all the construction parameters of the braid are aligned with those proposed by the analytical model.

The objective of this work is to present a model for the computation of the transfer impedance of HSD connector based on the finite element method (FEM). The advantages of this approach, as opposed to the analytical and empirical methods, are the ability to deal with complex materials and geometries. The transfer impedance of the developed FEM model is benchmarked against measurements.

II. COAXIAL CABLE TRANSFER IMPEDANCE CALCULATION AND MEASUREMENT

This section revisits the theoretical foundations necessary for interpreting physical phenomena associated with cable shielding. There are different analytical models available for the evaluation of shielding effectiveness. A summary of a known semi-

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empirical model proposed by Kley [7] is presented for a better understanding of the theory on a known problem. The following parameters define a braided shield:

m number of carriers,
n number of wires in each carrier,
d wire diameter,
D_0 diameter under the braid,
s lay length,

$D_m = D_0 + 2.5d$ average braid diameter,
$\alpha = \arctan(\pi D_m / s)$ weave angle ,
$G_0 = mnd / (2\pi D_m)$ minimal filling factor,
$G = G_0 / \cos(\alpha)$ filling factor,
$B = G(2-G)$ optical coverage.

The DC resistance of the braid per unit length can be calculated by using the equation:

$$R_{DC} = \frac{4}{\sigma mnd^2 \pi}\frac{1}{\cos(\alpha)} = \frac{1}{\sigma G_0 \cos(\alpha)}\frac{2}{\pi^2 D_m d}. \quad (1)$$

The shield transfer impedance is governed by:

$$Z_T = \frac{1}{I_S}\frac{dV}{dl}, \quad (2)$$

where Z_T is the transfer impedance in ohms per unit length, I_S is the shield current, V is the voltage induced between the internal conductors and the shield, and l is the length of the cable. The smaller the transfer impedance, the more effective the shielding.

Tyni's model [8] gives an equation for the transfer impedance of braided shield as:

$$Z_T = Z_R + i\omega L_T + (q+i)\omega L_S. \quad (3)$$

Z_R is the transfer impedance of a tube with a thickness of d [1].

$$Z_R \approx \frac{1}{\sigma G_0 \cos\alpha}\frac{2}{\pi^2 D_m d}\frac{d_R(1+i)\delta}{sh[d_R(1+i)/\delta]}. \quad (4)$$

Coupling inductance L_T and eddy currents inductance L_S are given as:

$$L_T \approx \frac{\mu_0}{m}[0.875\frac{\pi}{6}(2-\cos\alpha(1-G)^3)e^{-\tau_H}] - \frac{0.11}{n}cos(2k_1\alpha)].$$

$$\omega L_S \approx \frac{1}{\pi\sigma\delta}\frac{1}{D_m}[10\pi G_0^2(\cos\alpha(1-G)e^{-\tau_E} - \frac{3.3}{2\pi G_0}\cos(2k_2\alpha)].$$

$$d_R = 0.67d/\sqrt{\cos\alpha} \quad \tau_E = 12G\sqrt[3]{B^2 d / D_m}$$

$$k_1 = \frac{\pi}{4}[\frac{2}{3}G_0 + \frac{\pi}{10}]^{-1} \quad \delta = \sqrt{2/(\omega\mu_0\sigma)} \ (\mu_r = 1) .$$

$$\tau_H = 9.6G\sqrt[3]{B^2 d / D_m} \quad k_2 = \frac{\pi}{4}[\frac{2}{3}G_0 + \frac{3}{8}]^{-1}$$

Variable τ_H is the magnetic field attenuation factor of the chimney effect. The ωL_S term is used to account for eddy currents in the aperture's walls due to the magnetic field that penetrates the shield. Transfer impedance as the combination of two shields can be calculated by using equation [9]:

$$Z_T = \frac{Z_{T1}Z_{T2}}{Z_{S1} + Z_{S2} + j\omega L_{12}}. \quad (5)$$

Z_{T1} transfer impedance of outer shield,
Z_{T2} transfer impedance of inner shield,
Z_{S1} internal impedance of outer shield,
Z_{S2} internal impedance of inner shield,
L_{12} inductance of the shield to shield line.

The comparison of calculated values and measurement on equivalent cable are shown in Fig. 1. The result of measurement follows the analytical model up to a certain frequency, due to several reasons. First, the perfect quality of the shield with no manufacturing related faults is assumed. Also, measurement contains resonances in the line because of the mismatches and the finite length of the measurement sample. These resonances are not taken into account by the analytical model [10].

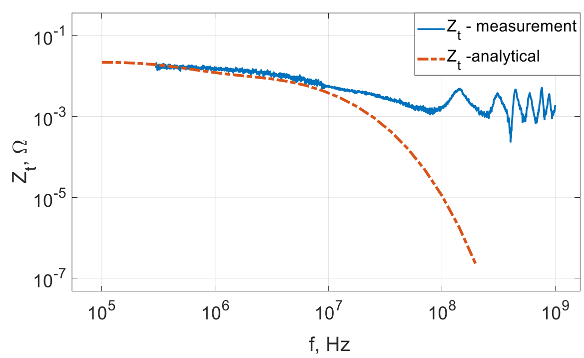


Fig. 1. Comparison of the calculated values of transfer impedance with measurement on a sample with m=16, n=8, $\alpha = 27$, $d = 0.1$ mm, $D_m = 3.3$ mm, $\epsilon_r = 2.1$.

In theoretical evaluations, the curve of transfer impedance is given as a single (deterministic) curve. In reality, that curve is greatly impacted by manufacturing tolerances.

Different shielding effectiveness values can be measured among different manufacturers and sometimes even among sample cables made by the same manufacturer [11]. Production tolerances, deviations in the manufacturing process, test sample preparation techniques or systematic errors can cause that behavior. Production tolerances on shield geometry parameters cause great changes in the values of shielding effectiveness [12]. For example, the optical coverage parameter of the shield is greatly affected by the carrier width. Equation (3) shows that the optical coverage parameter has a major effect on transfer impedance at a higher frequency range.

Even more accurate models and equations do not yield significantly better results and the divergence of measured and calculated values is significant. More accurate analytical models are useful for getting the dependence of optimal solutions on cable design constraints. Also, such models are used to determine the stability and sensitivity of the optimal solutions to the variations of the variables.

A more complex model was introduced by Latham [13], who developed equations that take into account the presence of nearby conductors, shield surface curvature and interaction between neighboring holes. Madle [14] introduced a coupling mechanism named "porpoising", which incorporates a special spirality effect to describe diffusion and aperture penetration.

The data obtained by these models is a great aid because it enables the manufacturing process optimization that leads to enormously improved shield effectiveness. However, even more complex analytical models can rarely evaluate the exact curve of the transfer impedance parameter that does not have a divergence from the measurement data [15].

III. HSD CONNECTOR TRANSFER IMPEDANCE SIMULATION AND MEASUREMENT

To take into account the complex geometry of a connector advanced numerical techniques and computational electromagnetics codes are employed. Transfer impedance was calculated by using numerical methods for the 3D model of the HSD connector shown in Fig. 2 and Fig. 3. There is no analytical solution for such geometry, therefore the use of numerical modeling is required [16]. For this simulation, a High Frequency Structure Simulator (HFSS) is employed. HFSS is 3D electromagnetic simulation software for designing and simulating high-frequency electronic products [17].

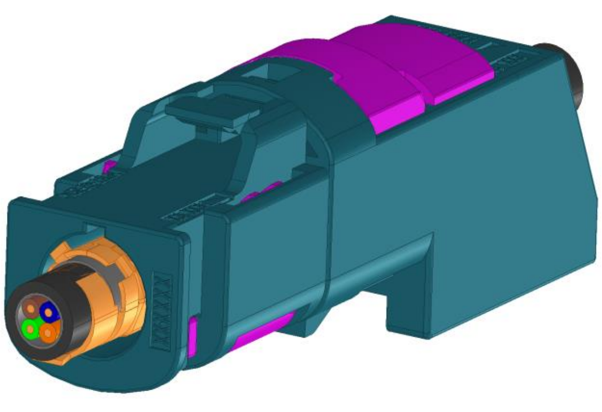


Fig. 2. A 3D model of HSD connector.

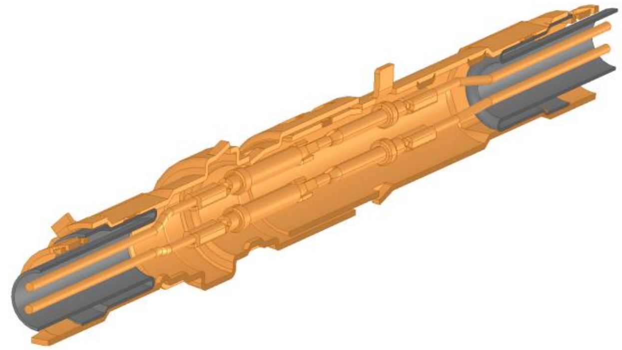


Fig. 3. Cross-section of shield and conductors in HSD connector.

In this case, a solution has to satisfy the given boundary and excitation conditions. Boundary conditions are defined by setting geometry properties in the model. A geometry defined as a perfect electric conductor represents a boundary where the value of tangential electric field is forced to zero. Excitations have to be correctly positioned and oriented to excite the desired model. If a solution that satisfies all of the boundary and excitation conditions is found, then the problem is solved.

The underlying idea of numerical calculation is to expand the unknown solution in terms of known expansion functions with unknown coefficients. The goal is to approximate unknown solution $f(x)$ by a sum of known expansion functions $f_i(x)$

$$f(x) \approx \sum_i a_i f_i(x), \quad (6)$$

where the coefficient a_i of each expansion function have to be such that the sum (6) approaches the function $f(x)$.

A. Setting up the model

By far, one of the most familiar and often used measurement setups for measuring transfer impedance is the triaxial tube in tube method [18]. While propagating through the shield, the EMI energy is attenuated by the shield. If the attenuation of the EMI energy passing through the shield is better, for the same magnitude of induced current I_S there is smaller dV generated by the same field so the shield is better. The parameter Z_t, as a result of voltage by current division, represents impedance per unit length. However, unlike the characteristic impedance, which determines the signal propagation properties along the cable, Z_T characterizes the energy propagation across the cable - through the shield [11].

A full developed assembly, equivalent to measurement setup for the triaxial tube in tube method setup is shown in Fig. 4. With defined excitations, the solver introduces electric field into the model area. Electric field couple to surrounding conductors and dielectrics through induced charges, currents and electromotive forces. From solver's point of view, created 3D model represents a problem of finding coupling mechanisms, parasitic interactions and distributed effects in the model. This problem is solved by finding approximate solutions to Maxwell's equations that satisfy specified conditions. To find such solutions the problem space is subdivided into elements, and then the magnitude of the assumed field at the junction of elements is found. The final solution is the sum of contributions from each element in a domain.

For the modeled problem, the HFSS software attempts to numerically solve the equation:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times E(x,y) - k_0^2 \epsilon_r E(x,y) \right) = 0, \qquad (7)$$

where:

$E(x,y)$ is a phasor representing an oscillating electric field,

k_0 is the free space wave number,

μ_r is the complex relative permeability,

ϵ_r is the complex relative permittivity.

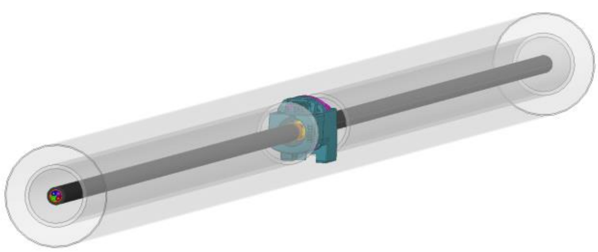


Fig. 4. FEM model of a cable-connector assembly of the triaxial method.

Treating shielding as a transmission line problem with both loss and reflection components as proposed by Ott [12] requires the solver to solve equation (7). For each frequency, a solution is given in the form of phasor $E(x,y)$, which after being multiplied by $e^{-\gamma z}$ becomes a traveling wave.

The internal circuit in a coaxial cable is usually matched to its characteristic impedance to improve the upper frequency limit because it minimizes the reflections in the system. For this measurement, all transmission lines were terminated in their characteristic impedance to avoid standing waves [19]. The common-mode characteristic impedance of the pair of contacts that was used to drive the connector shield was previously measured by using the time domain reflectometry and the results are shown in Fig. 5.

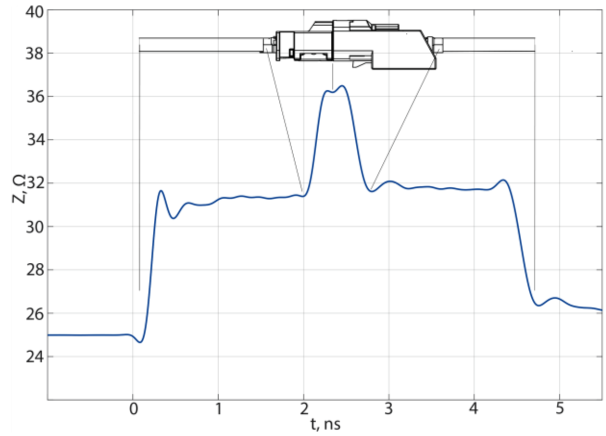


Fig. 5. TDR measurement of a system.

Results of measurement and simulation of the transfer impedance are shown in Fig. 6. At lower frequencies, the transfer impedance in the simulation is equal to the direct current (DC) resistance of the shield. At higher frequencies, the transfer impedance parameter increases with increasing frequency, and the effectiveness of the shield decreases because of the apertures in the shield. Transmission line effects are present up from frequency $f \approx 50$ MHz in measurement results and up from $f \approx 200$ MHz in simulated results. Transmission line effects are present because of the reflections that can never be fully eliminated. Reflections are created by changes in impedance, and the main cause of changes in impedance are transitions in the line's geometry. Primarily at the places where the connector is connected to the cable, and where male and female parts of the connector are connected.

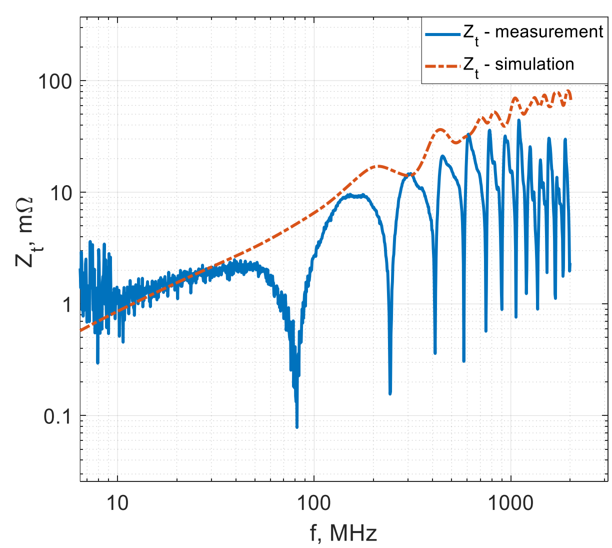


Fig. 6. Measured and simulated transfer impedance parameter of HSD connector.

Manufactured connector has production imperfections that cause discrepancies between simulation and measurement. Discontinuities caused by seams and small gaps, especially those between adjacent surfaces are hard to recreate in 3D model. At those areas, geometry is approximated. In spite of existing differences, the results are useful in design phase of connector.

Simulation data is analyzed with Feature Selective Validation (FSV) method [20-23]. The FSV method allows for objective, quantified comparison of data. It is widely used for validation and assessment of different models in computational electromagnetics. The FSV tool gives GRADE = 3 and SPREAD = 3 for FDM evaluation of the comparison in Fig. 6.

IV. CIRCUIT SIMULATION

The shield exhibits linear electric and magnetic properties, meaning that its performance does not depend on the amplitude of the currents and fields. The transformation data between voltages and currents ensures that wave effects are included in the circuit simulations, but only significant coupling can be transferred.

Extracted circuit model can be imported into a circuit simulator to explore various optimization strategies. For example, combining the connector with other lumped and distributed models for analysis of a larger system with satisfying level of accuracy. In this case, the shield is modelled as a multipole. The ratio of the voltage at one port of such circuit to the current at the other port is Z_{21}. In Fig. 7 the equivalent circuit of the modeled problem is presented, however, instead of S-parameters, Z_t is calculated by using the equation:

$$Z_t = \frac{V_{core}}{I_{shield}}. \quad (8)$$

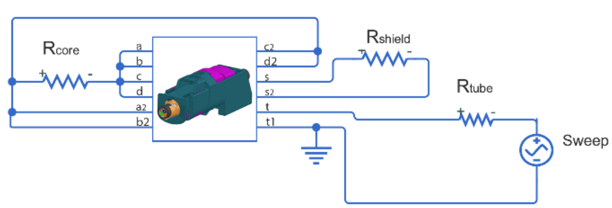


Fig. 7. Circuit model of a triaxial setup.

The computation result of the transfer impedance with circuit theory and its comparison against measurements and calculation with transmission line approach are shown in Fig. 8. The results of both models are in good agreement with the measurements.

A screened symmetrical multi-conductor cable is treated as a quasi-coaxial system as proposed in [24]. The conductors of all pairs are connected together at both ends. All screens, also those of individually screened pairs or quads, are connected together at both ends. The screens are connected over the whole circumference as proposed in [25].

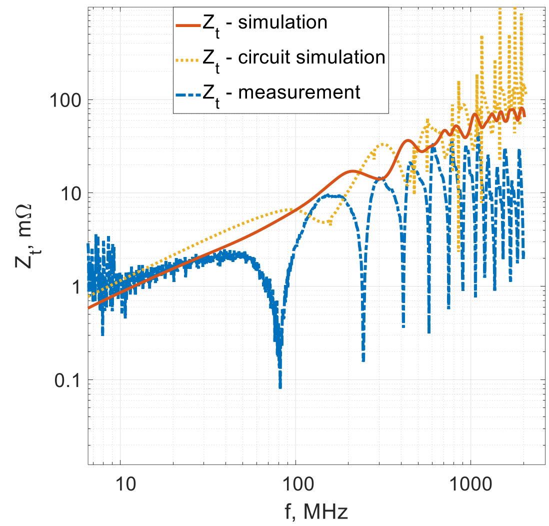
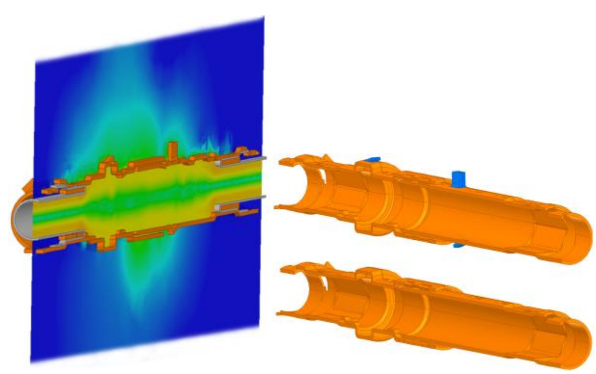


Fig. 8. Measured and simulated transfer impedance parameter of HSD connector.

Many mechanical and manufacturing related constraints affect the final design of the connector and the shield EMI performance. For example, some apertures in the shield of the connector are present because parts of the shield are designed as carriers for the plastic casing of the connector. Other problems are present because the shield is bent into the shape of a cylinder and it is not a seamless tube. Also, the thickness of the shield is primarily defined by mechanical properties, not by electrical properties.



(a) (b)

Fig. 9. Cross-section of the connector shield with plotted magnetic field and identified leakage spots.

Based on the field leakage shown in Fig. 9 (a) the worst parts of the shield were improved to see the possible improvement on the efficiency of the shield at the cost of plastic carriers being designed in another way. The cross section of the connector shields before and after modification is shown in Fig. 9 (b). An improved model, according to Fig. 9 (b) is simulated by using ANSYS HFSS and compared to the original model. Figure 10 shows the result of simulation with the modified model. As expected, the effectiveness of the shield increases due to the improvement in shield geometry.

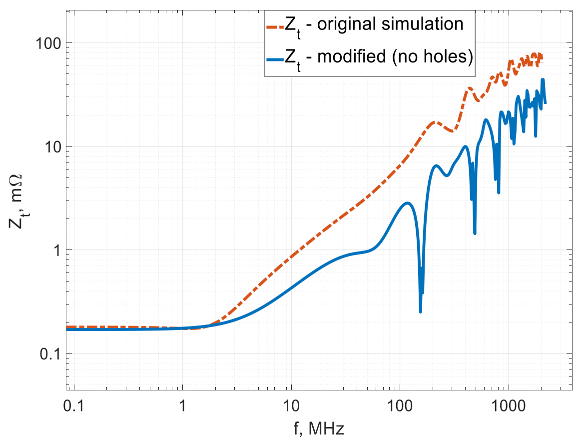


Fig. 10. Effect of shield modifications on transfer impedance.

V. CONCLUSION

A required step before starting the FEM analysis is the generation of CAD geometry to represent the actual device under test. Generating geometry for a braided wire shield, one of the most commonly used type of shields in the cable industry is a time-consuming task. There are numerous researches on creating complex geometries automatically by using different algorithms [26,27]. Also, tools and analytical models for the electromagnetic analysis of braided cable shields with general geometries are in constant development [28].

The complex geometry of the used HSD connector is considered in this paper. Due to complexity, there are no generalized solutions available. The presented work describes methods for the numerical calculation of the transfer impedance of such complex geometry by using FEM. One method is based on the simulation of scattering parameters while the other assumes that the connector is electrically small so that it can be modeled as a lumped element. Numerical solutions are not always suitable for a general analysis of the studied phenomena [29]. That is why the expansion of one numerical solution over a wide class of problems is not always possible. However, numerical solutions can be adapted to a range of connector sizes and different geometry configurations that use complex geometries and materials. Predicting the value of the transfer impedance of the connector shield before its manufacturing saves time and money. It allows the manufacturing process optimization based on the sensitivity of the shield performance to the changes of tolerances in specific parts. It also enables EMI performance optimization because of the possibility of testing a variety of different design possibilities before manufacturing.

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