Odd-Mode Impedance-Controlled Shielded Flat Flexible Cables for In-Vehicle Data Transmission

Volker Zwillich[1], Wolfgang Menzel[1], Lars Roehrig[2], Helmut Leier[3]

[1] University of Ulm, Department of Microwave Techniques, Ulm, Germany,
Volker.Zwillich@uni-ulm.de, Wolfgang.Menzel@ieee.org
[2]I&T Innovation Technology AG, Flat Cable Solutions, Siegendorf, Austria, L.Roehrig@innovation-technology.de
[3]DaimlerChrysler AG, Research & Technology, Ulm, Germany, Helmut.Leier@daimlerchrysler.com

***Abstract*— The application of flat flexible cables (FFCs) for data transmission in cars is investigated. Measurements and simulations of commercial unshielded FFCs indicate possible signal integrity problems for the transmission of high data rates. Newly designed shielded FFCs were fabricated in a cost effective extruding process with different dielectrics and various shielding concepts. They were characterized using time domain reflectometry to compare measured and simulated odd-mode impedances. The different shield types are evaluated with emission measurements of a high speed CAN connection.**

I. Introduction

The cable harness is the most expensive electronic component in modern cars and the manual assembling of the harness is cost intensive. Harnesses consisting of FFCs have several advantages over round cables. They require less space, laying and contacting can be automated, and their EMC properties are reproducible. Today, FFC harnesses are typically employed in roof interiors and doors for DC-power applications. Furthermore, there is a demand to apply FFC technology for data transmission in vehicles.

The odd-mode describes a propagation mode in a system with two conductors plus ground in which the two conductors have signals equal in magnitude and with opposite polarity. The odd-mode impedance is the impedance between one conductor and ground while the system is driven in the odd-mode. In this work, the odd-mode impedance and the crosstalk of commercial unshielded FFCs is determined. Newly designed shielded FFCs with different shielding concepts and dielectrics were fabricated and characterized. Finally, emission measurements were made to evaluate the different shielding concepts.

Previous work on crosstalk analysis of FFCs up to $100\,\text{kHz}$ includes work by Warner et al. [1]. Mortier et al. [2] measured the transfer impedance of shielded FFCs for various shield configurations, shield materials and thicknesses up to $1\,\text{GHz}$. Design rules for an FFC harness that are derived from crosstalk analysis are presented by Kosdikian et al. [3].

II. Unshielded FFCs

At first, the odd-mode impedance of a commercial unshielded FFC form I&T Innovation Technology was analyzed using quasi-static simulation [4]. Just like the situation in a vehicle, where the distance of an FFC harness to the grounded car body is usually not constant,

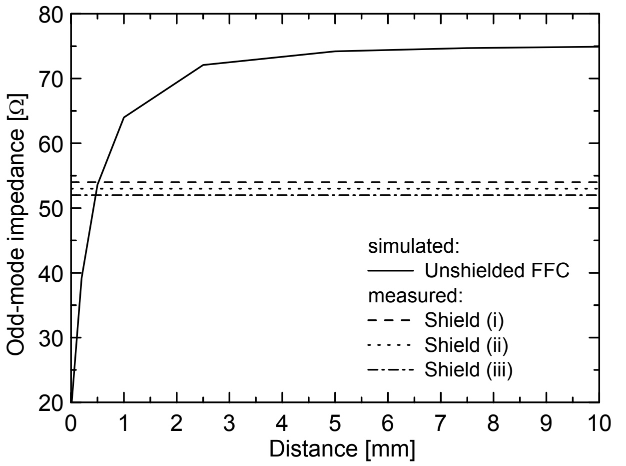


Fig. 1. Simulated odd-mode impedance as a function of the FFC-to-ground distance for an unshielded FFC. Measured Z_{odd} for 50-60 Ω FFCs with shield (i)-(iii).

the FFC-to-ground distance is varied in the simulation. As can be seen in Fig. 1, Z_{odd} is critically dependent on the distance to ground in the vicinity of the ground plane. Fig. 1 also depicts measured impedances for shielded FFCs shown in Fig. 5 which will be discussed later . Along the signal path of an FFC build into a car, odd-mode impedance steps and termination mismatches can occur. As a result, data signals can be reflected and they can interfere with each other.

In addition, near-end crosstalk (NEXT) measurements of two FFCs stacked on top of each other were performed up to $600\,\text{MHz}$ and compared to the frequently used unshielded twisted pair (UTP) wire (Fig. 2). NEXT-values for the unshielded FFCs are with $30\,\text{dB}$–for values up to $100\,\text{MHz}$–significantly larger than for the UTP cable.

Results above show that signal integrity problems can occur for unshielded FFCs in high-speed data applications. To overcome these limitations and still maintain the essential advantages, shielded FFCs are considered.

III. Design and Extrusion of Shielded FFCs

Odd-mode impedance-controlled shielded FFCs are designed using 2D simulation of the cross section depicted in Fig. 3. The simulated structure consists of two rectangular flat conductors of width w and thickness d which are surrounded by a dielectric. A fully surrounding metal shield encloses the dielectric. The conductor width of $w = 1.0\,\text{mm}$ ($d = 0.1\,\text{mm}$) and the pitch of $w + s = 2.54\,\text{mm}$ are chosen so as to remain compatible with existing

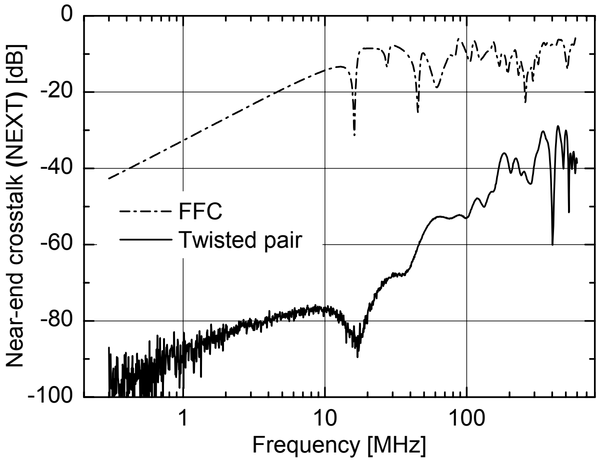


Fig. 2. Measured near-end crosstalk of two stacked FFCs compared to two twisted pair cables.

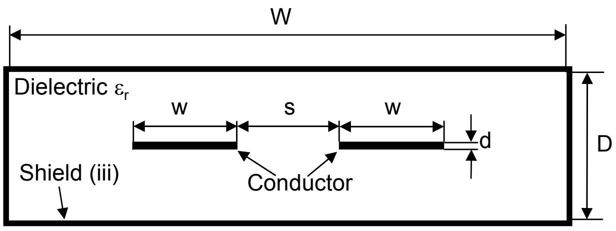


Fig. 3. Cross-sectional view of shielded FFC.

connector systems. The shield dimensions D and W are optimized to maintain a flat geometry and attain values for Z_{odd} of 50 - 60 Ω ($D = 2.23$ mm, $W = 5.88$ mm) and for Z_{odd} of 25 - 30 Ω ($D = 0.78$ mm, $W = 4.40$ mm). The influence of the dielectric constant on the odd-mode impedance is analyzed for both structures and will be discussed in the characterization section.

Shielded FFC samples were fabricated according to the designed dimensions using an extrusion process which is described below. The production process starts with the inner copper wires being unwound from a coil and lead to the first extruder. There, the inner wires are insulated from each other with melted granulate that is chosen depending on its dielectric permittivity. The dielectrics polypropylene (PP), high-density polyethylene (HDPE), cross-linked polyethylene (XLPE), foam of thermoplastic polyurethane (TPU) and air are used. The extruded flat cable is fed to a short water based cooling mechanism (Fig. 4).

Three different shieldings were applied to the FFCs

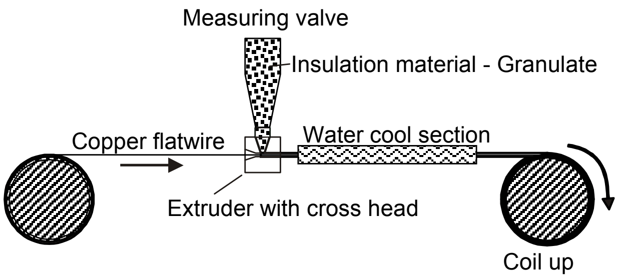


Fig. 4. Extrusion process: a flat wire is fed into an extruder where it is surrounded by melted granulates and finally cooled down.

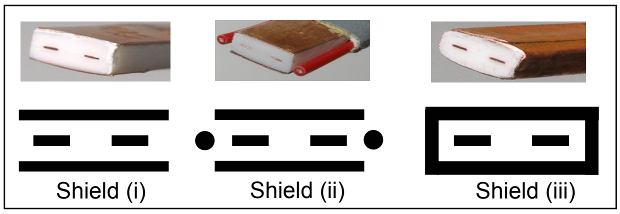


Fig. 5. FFC samples with three different shields were fabricated. The shield consists of copper foil that partially shields [(i) and (ii)] or fully surrounds the FFC (iii). The final coating process was not applied to these samples.

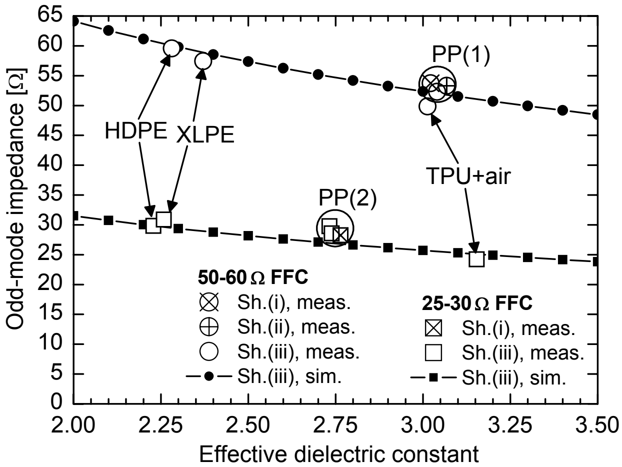


Fig. 6. Measured and simulated odd-mode impedance as a function of the effective dielectric constant for 25-30 Ω FFCs and for 50-60 Ω FFCs.

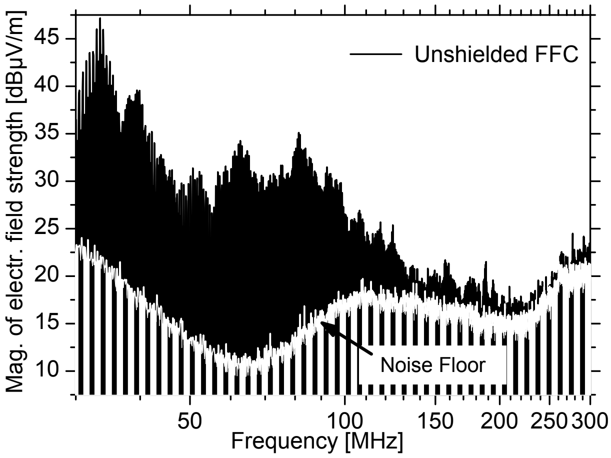
(Fig. 5). While there are different options to build a shield around a flat cable, copper tapes were chosen. The tapes are also unwound from coils and preformed in a forming tool outside of the second extruder. In an in-line process, they are then laid onto the already built inner part of the cable. Immediately after the shielding is attached, the assembly is fed into the next extrusion process where the tape is bent to its final shape and insulated by the coating. The following section cools the cable down to room temperature and–after quality control–the cable is wound up onto coils. It is important to mention that the described process consists of steps that are sequential and in-line, building only one process chain, and thereby producing a cost-effective shielded flat cable.

IV. Characterization

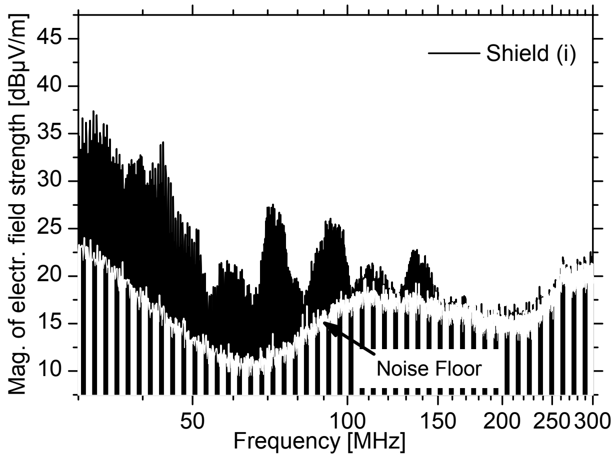
The odd-mode impedance of the FFC samples and the one-way signal delay τ were measured using differential time domain reflectometry. Neglecting the low dielectric losses, the effective dielectric constant can be determined by

$$\varepsilon_{\text{r,eff}} = \left(\frac{c_0}{c}\right)^2 = \left(\frac{c_0 \tau}{l}\right)^2 . \tag{1}$$

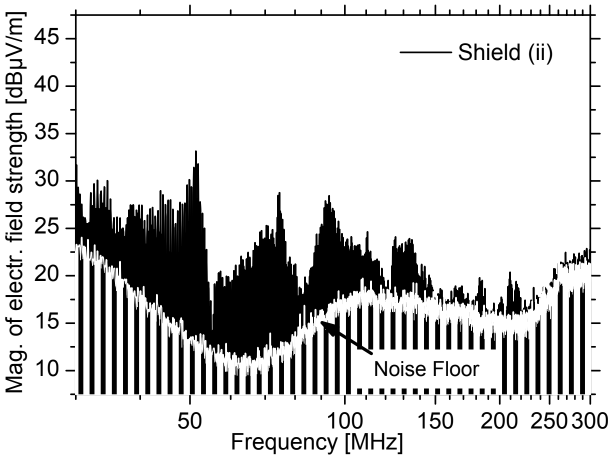
Where c_0 represents the speed of light, c the velocity of propagation for the odd-mode, and l the length of the FFC samples. Fig. 6 depicts simulated and measured odd-mode impedance values of FFCs with different dielectrics and different shields as a function of the effective dielectric constant. The measured and simulated values for Z_{odd} decrease with an increasing effective dielectric constant



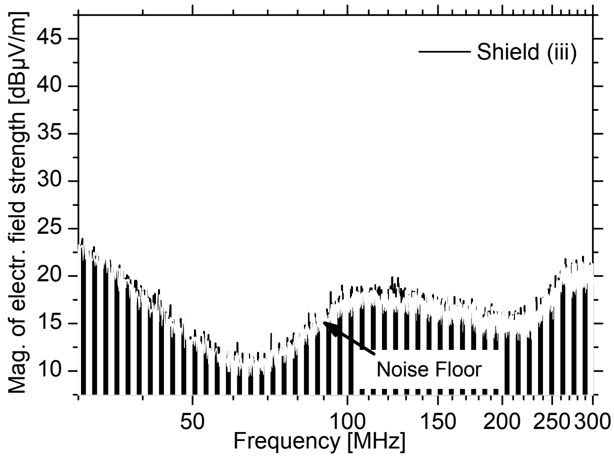
(a)



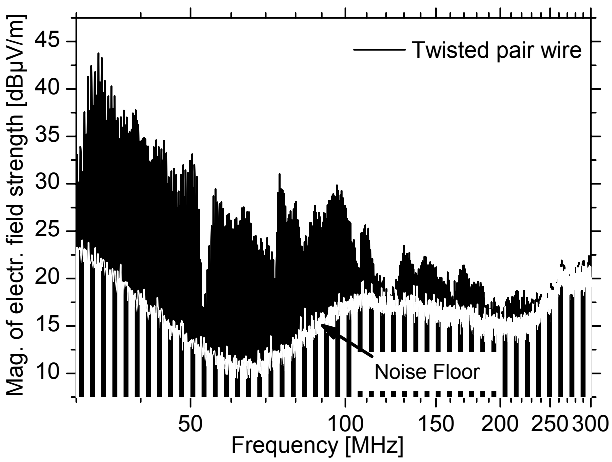
(b)



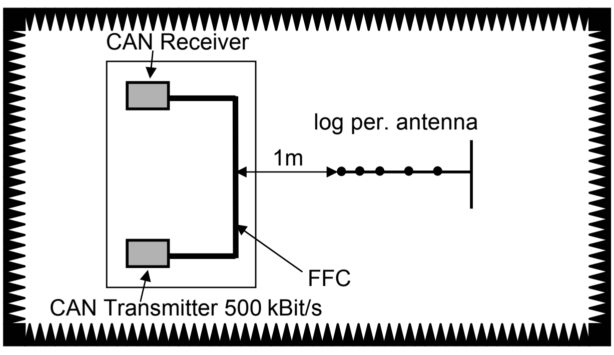
(c)



(d)



(e)



(f)

Fig. 7. Measured emission level as a function of frequency for two high speed CAN nodes connected with an unshielded FFC (a). (b) – (e) depict the emission results for shield (i) – shield (iii) and for a twisted pair wire, respectively. The measurement setup in the anechoic chamber is illustrated in (f) (top view).

as expected from transmission line theory. The measured results indicate that a change of the shield geometry from shield (i) to (iii) for the same FFC has little influence on Z_{odd}. Only a small fraction of the odd-mode field penetrates through the gap at the sides of the FFC in the case of shield (i) and (ii). Simulated and measured odd-mode impedances correspond for the various dielectrics. Differences between $\varepsilon_{\text{r,eff}}$ values of the same material type for the 25-$30\,\Omega$ FFC and for the 50-$60\,\Omega$ FFC are small for the materials HDPE, XLPE, TPU/air foam ($|\Delta\varepsilon_{\text{r,eff}}| < 0.15$). They are about twice as much for PP ($|\Delta\varepsilon_{\text{r,eff}}| = 0.30$). While the smaller deviations can be explained with measurement uncertainties, the deviations for PP can result from a change in the electrical properties of the material due to the different extrusion thickness. The obtained dielectric constants for the different materials is useful information for future simulations of FFCs.

As expected, the ground dependence of Z_{odd} for FFCs with shield (i)-(iii) is eliminated as depicted in Fig. 1. To evaluate the effectiveness of the different shields, electromagnetic emission measurements were performed according to CISPR 25 [5]. Two high-speed CAN nodes operating at 500 kBit/s are connected via the different 50-$60\,\Omega$ FFCs. Due to asymmetries in the CAN communication path (e.g. bus driver), a common mode field is generated that couples from the FFC to the logarithmic periodic measurement antenna. The emission levels for unshielded and shielded FFCs are presented in Fig. 7 and compared to a twisted pair wire. The plotted emission levels are obtained from measurements with a vertically polarized antenna using a test receiver in peak detection mode. Similar results were observed with a horizontally polarized antenna. The measurement setup in the anechoic chamber is illustrated in Fig. 7(f).

The peak emission at $33\,$MHz for the unshielded FFC is reduced with shield (i) by $10\,$dB and with shield (ii) by $15\,$dB. No emission above the noise floor can be seen with shield (iii) which is a reduction of more than $25\,$dB. The emission level of the twisted pair wire is only about $4\,$dB lower compared to the unshielded FFC.

V. Conclusion

The results indicate that unshielded FFCs can cause signal integrity problems due to crosstalk effects and odd-mode impedance fluctuations. To overcome these drawbacks, odd-mode impedance-controlled shielded FFCs are designed, manufactured, and characterized. Simulated and measured impedances agree well with each other. Partially shielding the FFC and adding drain wires improves the EMC behavior and eliminates the critical ground dependence of Z_{odd}. However, a full surrounding shield is necessary for effective electromagnetic screening.

References

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