Cable Harness EMC/EMI: Cross Talk, Radiation, Interference and Susceptibility

Introduction

Bundles of electrical cables in vehicles, aircraft, ships and buildings pose electromagnetic compatibility and interference challenges to the electrical design engineer. Due to their lengths, they are more likely to radiate or pick up irradiation than many other electrical components and systems. Through several examples, this white paper will discuss how those challenges can be met with the aid of electromagnetic simulation.

EMC/EMI Challenges with Cable Harnesses

Electronic systems in vehicles, aircraft, ships and buildings are often connected by means of electrical cables. Without exaggeration, a modern automobile, due to the proliferation of electrical systems, contains several kilometers of electrical wiring, bundled in a large number of so-called harnesses. This is even more the case for aircraft. Design engineers have to ensure, well before the first prototype is built, that many kinds of electromagnetic compatibility (EMC) and electromagnetic interference (EMI) problems be avoided. Such problems include:

- Digital signals on one cable may exhibit cross talk with those on another cable
- Radiation or near fields from a cable may exceed regulations
- Irradiation from strong nearby sources, including from a lightning stroke, may be picked up by a cable harness and delivered to sensitive electronic equipment

Design engineers need to perform electromagnetic simulations at an early stage in the design process. FEKO is the appropriate tool because it is a general-purpose 3D electromagnetic simulator that contains a dedicated cable-analysis module. A general-purpose 3D simulator is essential because of its ability to analyze the behavior of fields and waves in a geometry of any shape and any material. The dedicated cable-analysis module is needed because this is the only way to predict signal propagation on cable bundles efficiently. FEKO combines both and links the currents in and on the bundles bi-directionally with the electromagnetic fields in the 3D environment.

In all these cases, the simulations are done in the frequency-domain. For cross talk and radiation involving digital signals, we will show how to take the spectrum of such signals into account. This is essential in order to compare results with international regulations, such as CISPR-25 and FCC Part 15. To analyze the impact of lightning, we will demonstrate how one can convert results to the time domain within FEKO itself. In the end, it is relatively straightforward for design engineers to explore different routing strategies and to determine how much shielding to apply without adding too much weight.

Cross Talk

The model used in the case study is shown in Figure 1. There are two cable harnesses in the car, as well as an antenna integrated in the rear windshield. The cable harnesses each contain two differential pairs, as shown in the cross section in Figure 2.

Figure 1: Model used in the case study

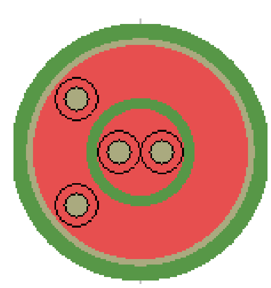

Figure 2: Cross section of a cable harness

In the FEKO simulation, initially a differential voltage of 1 V is applied to one of the differential pairs, and a frequency sweep is performed. The result of such a simulation is, among other things, the cross talk between differential transmission lines, both within the same harness and between harnesses. Figure 3 shows the near-end cross talk (NEXT) and far-end cross talk (FEXT) that results between differential pairs in different harnesses, after the fields have interacted with the entire 3D structure.

Note that the cross talk is mostly well below 1 mV, but several resonances occur. The first resonances are at 34 and 38 MHz. At 34 MHz, the aggressor radiates strongly, while the victim is only moderately receptive. At 38 MHz the victim, which has a different electrical length, is highly susceptible while the aggressor radiates only moderately.

For cross talk, three components are needed: an aggressor that radiates, a victim that receives, and a path between them. In this case, a field plot is very revealing. Figure 4, in which no source is connected to the antenna (the antenna is entirely passive), shows that the windscreen antenna is an essential part of the path.

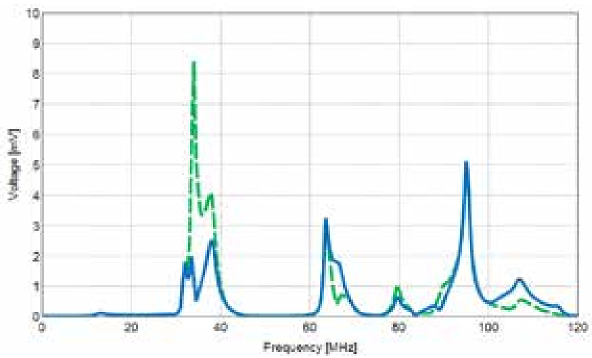

Figure 3: Differential cross talk between harnesses. Blue solid line: NEXT. Green solid line: FEXT

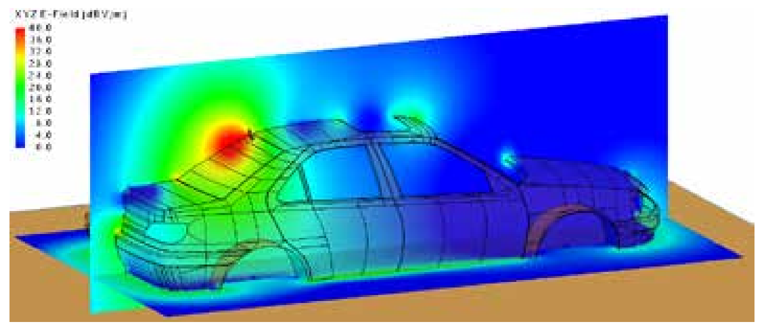

Figure 4: Fields at 34 MHz due to a differential aggressor

This was verified by running the simulation again without the antenna present. Strikingly, while a cross talk of 8 mV was reached in Figure 3 with the receiving antenna present, the maximum (in the frequency range below 40 MHz) was only 0.025 mV when the antenna was removed: a reduction of 50 dB! This underscores the need for EMC testing of the entire vehicle. While individual systems may appear safe, problems appear when the entire system is put to the test.

Since EMC measurements of the entire vehicle can only be done late in the design process, when modifications are costly, it is essential to identify and fix EMC problems by means of simulation software early in the design process.

Radiation

As had been mentioned, in the FEKO simulation initially a differential voltage of 1 V is applied to one of the differential pairs, and a frequency sweep is performed. Figure 5 shows the maximum electric-field magnitude at 10 m as a function of frequency, based on an excitation with a differential voltage of 1 V (0.5 V per signal line) at every frequency. In order to compare this result with regulations, it needs to be weighed with respect to the spectrum of the actual signal on the differential line.

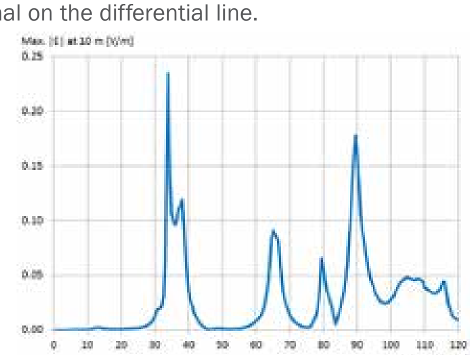

Figure 5: Maximum E field at 10 m distance as a function of frequency

Unintended radiation from electronic systems within a vehicle requires compliance with international regulations (e.g. CISPR 25) [1, 2]. Unintended radiation from general electronic systems requires compliance with similar regulations (e.g. FCC Part 15 [3]). To investigate compliance, proper accounting will have to be made for the spectrum of the digital signal.

Let the signal on the differential transmission line be a 2 Mbit/s digital signal with a rise and fall time of 100 ns. The equations for the resulting spectrum can be found in [4].

For a 5 V differential clock signal (2.5 V per signal line), the resulting radiated field at 10 m is presented in Figure 6a. Note that the spikes occur at the odd harmonics of 2 MHz. Also note that no harmonics are visible at 10, 30, 50, … MHz. This is due to a sinc function involving the rise time. The radiation at 34 MHz, a resonance due to the electrical length of the cable, exceeds the radiation at all other frequencies in both plots. The FCC Class A limit at 34 MHz is 39 dBµV/m at 10 m. Clearly, the limit is exceeded by a significant amount.

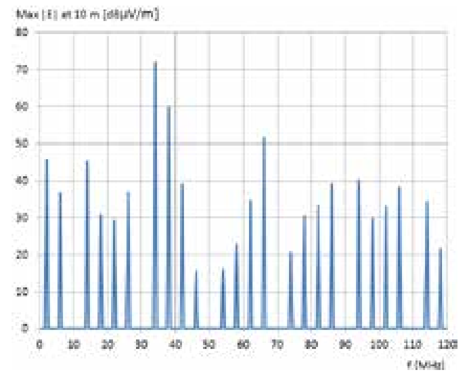

Figure 6a: Maximum |E| at 10 m for a 5V differential clock signal

For a 5 V differential pseudo-random binary sequence (PRBS), the resulting radiated field at 10 m is presented in Figure 6b. A receiver bandwidth of 120 kHz [1] has been used.

The radiated emissions of the PRBS are a lot less worrisome than those of the regular pulse, simply because the PRBS spreads its radiated power over all frequencies. Still, at 34 MHz the limit of 39 dBµV/m is exceeded.

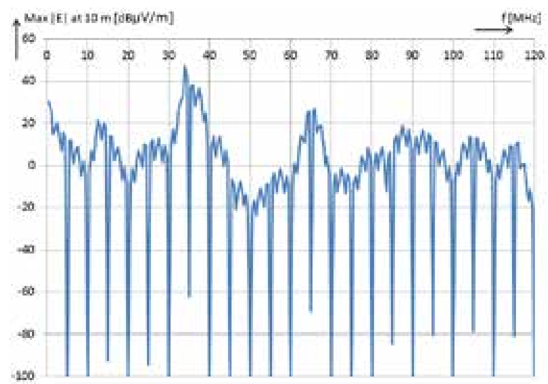

Figure 6b: Maximum |E| at 10 m for a 5V differential PRBS

In order to comply with regulations, the cables will need to be shielded. The main benefit of these simulations is that they reveal how much shielding is needed to achieve first-pass success in tests. This is important, since repeated testing is expensive, while adding too much shielding to all the cable harnesses in a vehicle adds a lot of weight and reduces the routing flexibility.

FEKO enables the user to specify several types of shielding: selected from a database of popular cable types, solid shields with a specified material and thickness, user-defined by means of the frequency-dependent impedance transfer matrix, and braided shields. For a braided shield (Figure 7) one specifies the relevant parameters and materials of the weave pattern, upon which FEKO determines the frequency-dependent transfer matrix using the Kley formulation [5, 6]. This formulation accurately models the coupling mechanism due to the field penetration through the shield apertures.

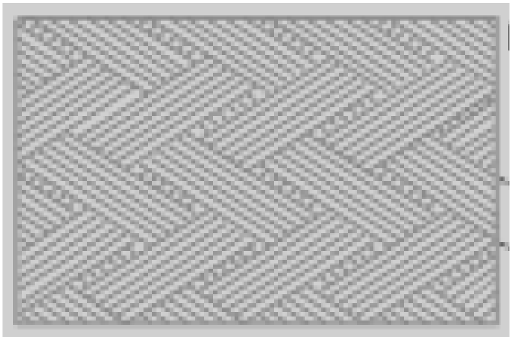

Figure 7: Braided shield

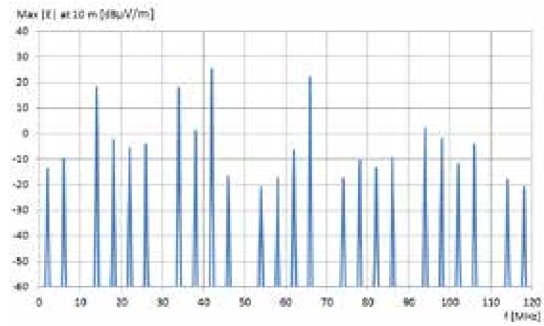

Figure 8: Maximum |E| at 10 m for a 5V differential clock signal in a shielded cable

With a shield of 32 carriers of seven 0.12-mm filaments each around each cable, which, for a shield radius of 5 mm leaves openings, the radiation is reduced sufficiently (see Figure 8) to satisfy the FCC regulations, if they were applied to vehicles. While CISPR-25 applies to automotive systems, it is used more for individual systems and harnesses than for radiation from entire cars. CISPR-25 limits between 30 and 54 MHz range from 22 to 46 dBµV/m at 1 m distance, depending on the class, which corresponds to 2 to 26 dBµV/m at 10 m distance. The individual system with harness might well pass in a standard test, while with the windshield antenna (a passive resonator) present the radiation, as shown in Figure 8, might be too high.

The difference in levels between Figures 6a and 8 (without and with shielding) varies with frequency. One reason for the frequency dependence is that the shielding factor is frequency dependent; another reason is that with the added shield the cross section of the cable has changed, so the amount of cross talk to other signal lines in the cable has changed. The latter is strongly frequency dependent.

Next, we take a closer look at the effect of the radiation on receiving systems within the same vehicle. The model (Figure 9) is essentially the same as before, but the windshield has been made more visible. We emphasize that, in all scenarios discussed in this paper, the dielectric layers of the windshield are included.

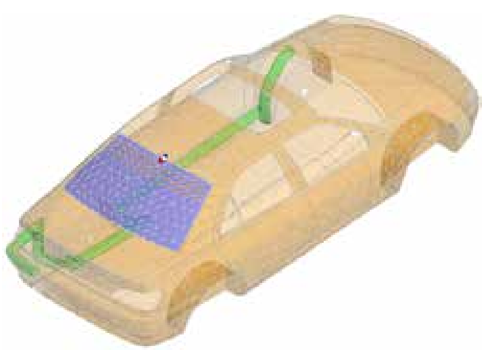

Figure 9: Model used in the case study

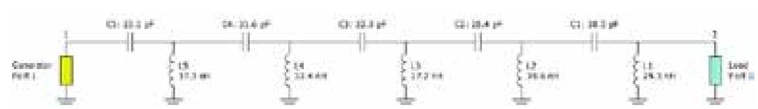

Figure 10: Matching circuit designed with Optenni Lab and integrated in the FEKO model

Windscreen antennas are typically embedded in a number of dielectric layers of varying dielectric properties. For such antennas, FEKO includes a Method-of-Moments based formulation that meshes only the metallic antenna elements in a windscreen antenna, while rigorously taking all dielectric layers into account with special methods. This avoids having to mesh the layers with a triangle size of the order of the layer thickness, which would lead to long simulation times.

In this study, the antenna is connected, in the integrated FEKO Schematic View, to a ten-element matching circuit (Figure 10) that provides a good match (S11 ≤ -23 dB) between 89 and 91 MHz. The matching circuit has been designed with Optenni Lab™.

Figure 11 shows the received voltage that passes the matching circuit when the differential signal is a 5-V regular binary pulse with repetition frequency 2 MHz and with rise- and fall times of 100 ns. The maximum is 8 dBµV. CISPR-25 [1, 2] specifies a maximum of 6 dBµV. This means that one either has to shield the bundles better, or work with a lower voltage, or ensure that this kind of signal can never travel on this cable. The result of Figure 11 was produced with the braided shield of the previous example. It will be straightforward to replace it with a shield that has a higher density of filaments, simulate again, and ensure that the requirements are satisfied.

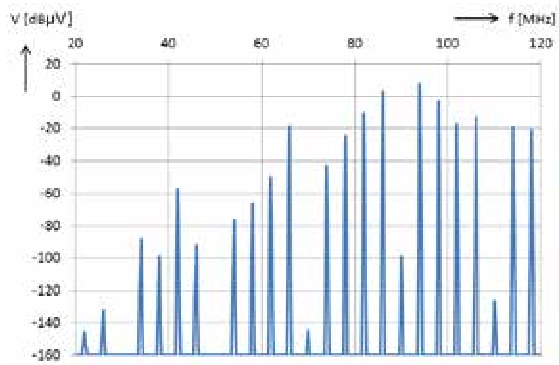

Figure 11: Voltage received by antenna and passed by the matching circuit

Lightning

A different type of EMI problem is caused by lightning. The strong fields associated with the lightning strike will induce currents in electrical cables, which then are delivered to (possibly sensitive) electronic systems.

In this case study, we will work with the aircraft model shown in Figure 12. This model represents the way susceptibility to lightning would be investigated experimentally in a laboratory. Similar to a laboratory experiment, three electrical cables of length 3 m each are placed inside the fuselage. The distance between any cable and the nearest metal surface is 10 cm.

Figure 12: Aircraft model mimicking a laboratory setup

When selecting the optimal numerical method, engineers must first decide whether to perform the simulation in the frequency or time domain. Lightning is by its nature a time-domain phenomenon. However, a practical problem manifests itself when performing simulations in the time-domain. In the finite-difference time-domain (FD-TD) and finite integration technique (FIT) methods the time step is governed by the level of detail present in the model [7,8]. For a typical aircraft model excited by a lightning pulse, the number of time steps becomes prohibitive. It will be better to simulate in the frequency domain and convert results to the time domain.

The choice for FEKO for this application is guided by the following considerations:

- frequency-domain analysis (time-domain analysis requires too many time steps for lightning)
- exceptionally low noise floor
- reliable simulations down to a few Hz
- efficient cable-bundle analysis
- schematic capability to add sources, components, terminations and probes
- time-analysis capability in the post processor

Standard IEC-62305-1 [9, 10] recommends the following current profile:

$$i = \frac{i_{\max}}{k} \cdot \frac{(t/\tau_1)^n}{1+(t/\tau_1)^n} \cdot \exp(-t/\tau_2) \qquad (1)$$

with

i_{max} = 200 kA
k = 0.93
T_1 = 19 µs
T_2 = 485 µs
n = 10

This profile has a fast rise and a slow decay (Figure 13). It is similar to the well-known double exponential, but avoids the unphysical abrupt change that the double exponential exhibits in the beginning. The frequency-domain simulation included frequencies from 10 Hz to 3 MHz.

Figure 14 shows the currents at the terminals of the three cables. In Figure 14a, the cables are unshielded, and induced currents exceed 1 A. This may well be too much for a sensitive system. Note that the induced current reaches its maximum when the lightning pulse has its fastest rate of change.

With a shield of eight carriers of five 0.2-mm filaments each around each cable, which, for a shield radius of 2.3 mm leaves significant openings, the lightning-induced current is reduced by almost a factor of 60, or about 35 dB (Figure 14b).

A brief induced current of 20 mA is significant, but is unlikely to cause system malfunction for most systems. The selected shielding can thus be regarded as the minimum amount of shielding that should be included in the design to protect against lightning.

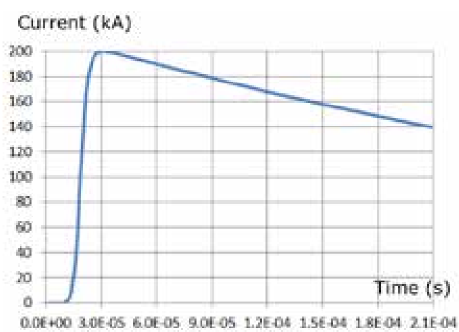

Figure 13: Lightning current profile

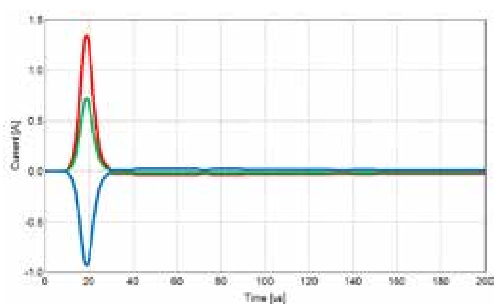

Figure 14a: Induced currents at the cable terminals before shielding is applied

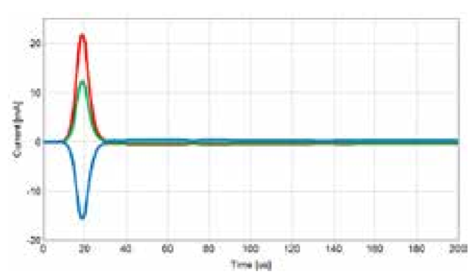

Figure 14b: Induced currents at the cable terminals after shielding has been applied

Note how these time-domain results can be obtained in a straightforward manner from the frequency-domain analysis. As mentioned before, a time-domain analysis can take a prohibitively long time in a lightning application, in comparison with the time needed to obtain the necessary frequency samples, as was done here. At this point different pulse shapes can be evaluated from the same frequency-domain results without having to perform a new simulation.

Conclusion

In this paper, we have shown by means of practical examples how FEKO can be used to prevent EMC/EMI problems in vehicles and aircraft with electrical cable harnesses. In all cases, the simulations are done in the frequency domain. For cross talk and radiation involving digital signals, we have shown how to take the spectrum of such signals into account. To analyze the impact of lightning, we have demonstrated how one can convert results to the time domain within FEKO itself. In the end, it is relatively straightforward for design engineers to explore different routing strategies and to determine how much shielding to apply without adding too much weight.

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