A Fast Radiated Emission Model for Arbitrary Cable Harness Configurations Based on Measurements and Simulations

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Abstract— **Within a functional EMC simulation for automotive component tests, the cable harness shows significant influence to the radiated emissions. Detailed harness models can be generated with the help of a full wave simulation within the frequency range. However, the calculation process is a very time intensive task, especially if the complete setup in respect to CISPR25 for radiated emissions is considered. With the help of one simplified simulation and auxiliary calibration measurements, it is possible to speed up the model generation process of the harness and to consider the ambient measurement structures. The method is presented for different harness structures and tested for assemblies with up to ten wires.**

Cable harness, harness radiation, component simulation, transfer function, functional emc simulation

I. INTRODUCTION

Functional EMC simulations for automotive components can help to reduce and understand electromagnetic phenomena within an early state of the development process. Especially the increasing number of electronic devices within vehicles as well as the need for lower limit values for radiated emissions lead to the demand for early EMC statements. Before an electronic component or module can be set up within a vehicle, the component is tested in accordance to the CISPR25 [1] regulatory standards, describing radiated and conducted emissions.

Usually, every simulation tries to take into account the real measurement structure as good as possible. Thus, every part of the component system as well as auxiliary measurement structures like stabilization networks and antennas have to be considered. In general, a component system can be divided into three sub models: the control unit, the cable harness and the load box (sensor, actor) or load simulator. For functional simulations of the control unit and the load, a lot of models for integrated circuits are available in Spice, Saber or IBIS format. It is also possible to include the printed circuit board into the simulation with the help of the PEEC Method or a full wave simulation [2].

However, there are no general models available, within functional network simulations, for the connected cable harness. Especially, if additional information like radiated emissions are required. An overview of the available methods, on how to consider radiation for harness models, is given in section III.

As a result of the given setup in accordance to CISPR25, radiated emissions from components or modules, the surrounding measurement equipment have to be considered to calculate the occurring radiated emissions. The setup consist mainly of the global ground plane, the ground plane of the table, the antenna setup and the harness itself, placed within an anechoic camber. Only a detailed full wave simulation can consider all surrounding structures, especially if different kinds of receiving antennas are used. Unfortunately, a detailed simulation will generate a high number of unknowns and thus result in a long simulation time.

With the help of auxiliary measurements it is possible to reduce the calculation time to a minimum and to speed up the model generation approximately by a factor 100 - 500 (dependent of the used simulation computer). The simulation model is hereby reduced to a model only including the harness itself, an auxiliary monopole as field receiving structure and a PEC (perfect electronic conductor) plane. Due to the removed mesh triangles of the ground plane and the antenna structure the simulation can thus be carried out very fast. The measurement structure contains one single wire, called as calibration wire, as well as the auxiliary monopole and the antenna structure of interest. Within the measurement it is possible to find the transfer function K(f) between the auxiliary monopole and the receiving antenna and thus combine the measurement and simulation setup. With the received transfer function K(f) it is now possible to extrapolate every simplified simulation to the real measurement setup. The proposed method is presented for harnesses with up to ten wires and verified for 0.3 - 1000 MHz. All considered full wave simulations are carried out with the Method of Moments (MoM) [3].

II. MODEL STANDARDS

To apply a functional EMC simulation within a network simulation, the employed harness model has to represent the real structure as good as possible. With the port parameters of the harness Z, Y or S parameters, it is possible to describe the electrical behavior of the structure. These parameters are necessary to evaluate the transmission performance of the harness structure as well as to evaluate signal integrity of transmitted signals e.g. CAN signals. To evaluate radiated emissions in respect to the setup for components and modules, the harness models have to supply additional information about the radiated field strength. Radiated emissions are considered up to 1000 MHz. Thus, the gained models should cope with the demands for conducted emissions (0.15 – 108 MHz) and radiated emissions (30 – 1000 MHz). The frequency range for radiated emissions is divided in different measurement setups for the monopole, the biconical and the log-periodic antenna structure.

The models are required to be stable and passive over the whole frequency range. Otherwise no transient simulations are possible.

III. METHODS TO CALCULATE THE HARNESS RADIATION

Before the radiation process can be considered for the harness model, it has to be ensured that the internal parameters are available. The internal or electrical parameters can be described with [Z], [Y] or [S] parameters with the dimension [2n x 2n], whereas n represents the number of conductors within the harness. With the help of the transmission-line equations, the electrical parameters of the harness can be described [4]. It is also possible to employ a full wave 3D simulation with the help of the known methods of MoM or FEM (Finite Element Method).

To describe the radiated emission, caused by the excitation of the harness, different methods are available to predict occurring radiation:

A. Common-Mode Radiation

If the electrical parameters of the harness structure are available and used within a simulation, it is possible to estimate the radiated emission out of the common-mode current or the total current. It is assumed, that the common-mode current is mainly responsible for radiated emission. Thus, if the common-mode current is known, the radiated emissions can be calculated. The method is proposed in [5]. However, the method is limited to common-mode radiation and only an estimation, without concerning the measurement setup in general.

B. Full Wave Simulation

With the help of a full wave simulation (MoM, FEM), it is possible to consider the complete measurement setup. Besides the electrical parameters, radiated emission can be predicted for multiple emission points or the receiving measurement structure can be included. Compared to the method in A, a full wave simulation requires a very long simulation time due to the detailed replication of the setup. An employed MoM calculation will generate about 40,000 to 60,000 unknowns and thus takes about five to seven days calculation time on an established simulation computer with a frequency resolution of 2 MHz.

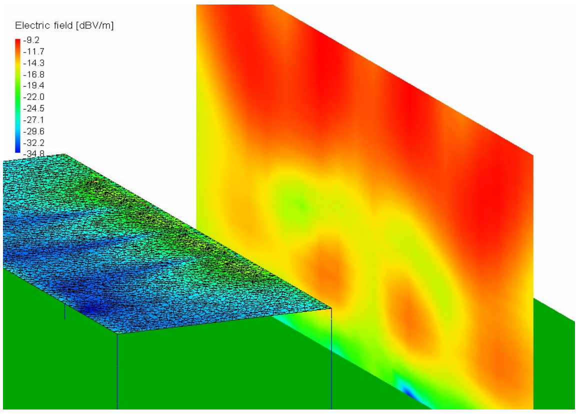

Figure 1. Full wave simulation of the complete setup with near field calculation of the radiation

Figure 1 shows the general setup for a full wave simulation with a near field calculation in 1 m distance to the harness. The harness is placed on the conducting table, 10 cm in front of the table edge. The calculation time is mainly slowed down due to the huge amount of mesh triangles, generated by the table structure.

C. Combining Measurement and Simulation

All previous methods can not describe the general setup, described in CISPR25, or result in a very long calculation time. If a simplified simulation is combined with calibration measurements, it is possible to take the complete setup into account and to speed up the model generation process. The simulations and measurements are combined with the help of a simple auxiliary monopole antenna, which is included in both setups.

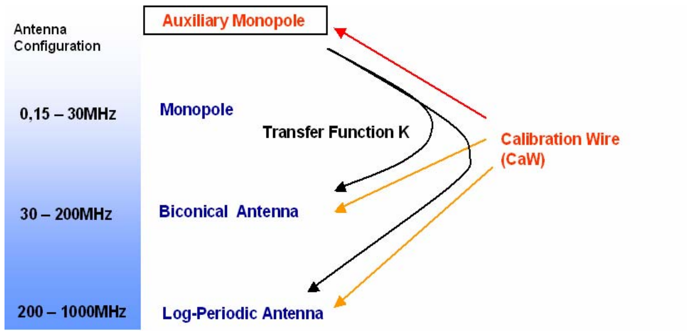

Figure 2. Measurement setup to determine the transfer function K(f)

For the calibration measurement one calibration wire is needed. The wire is placed at the same position as the following cable harness. With the results of a three port scattering parameter measurement, the transfer function K(f) between the auxiliary monopole and the considered receiving antenna can be found within the frequency range of each antenna as shown in figure 2. The transfer function K(f) is herby defined with the measured scattering parameter as:

$$K[dB] = S_{Antenna\text{-}CaW}[dB] - S_{AuxMonopole\text{-}CaW}[dB] \tag{1}$$

The transfer function represents the coherence between the sensitivity of the auxiliary monopole and the receiving antennas. The radiation amount of the harness to the auxiliary monopole is transferred to the measurement structure of interest.

Due to the simplicity of the used monopole it is easy to build up the same monopole within the simulation. All information about the environment and used receiving antennas are now concentrated within the transfer function. The simulation setup can thus be reduced to a minimum, considering only the cable harness and the auxiliary monopole. Even the table structure can be removed within the simulation by a PEC plane, like shown in chapter V.A.

If the radiation amount of the harness to the monopole is known out of the simulation, the radiation to the real measurement setup can be calculated with the transfer function K(f).

$$S_{Antenna\text{-}Harness}[dB] = S_{AuxMonopole\text{-}Harness}[dB] + K[dB] \quad (2)$$

The transfer function has to be determined for every type of antenna and polarization.

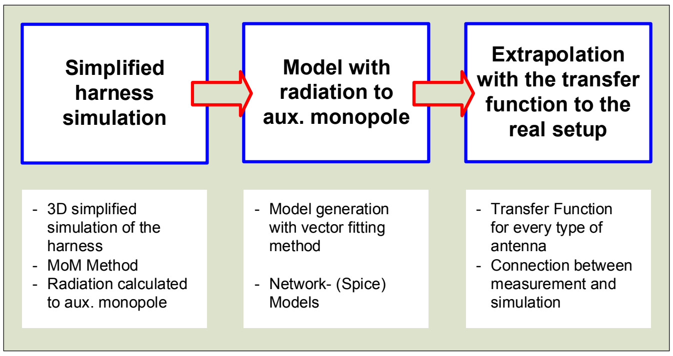

Figure 3. Workflow to generate the radiation model

Figure 3 describes the general workflow for the model generation process. Fist the harness radiation is simulated within an simplified 3D simulation. In the next step, it is possible to create an appropriate network model, including the radiation information to the auxiliary monopole. The last step extrapolates the result out of step tow to the real measurement setup with the help of the measured transfer function.

In the following, the method is presented for the biconical antenna with vertical polarization.

IV. General Setup

The setup for the harness is mainly in accordance to the setup described in CISPR25. The harness and the calibration wire are placed on a grounded table, 10 cm in front of the table edge. The distance between the cable harness and the reference point of the antenna is 1 m, with a height of the biconical and log-periodic antenna of 1 m above the ground plane. The auxiliary monopole is directly placed on the table 1 m behind the harness. The harness length is chosen as 2 m in accordance to CISPR25. The difference to the standard setup is the harness placement. Whereas the standard setup describes a double-sided bent harness, the chosen setup concentrates on a straight harness as shown in figure 4. A bent harness configuration would lead to a higher variance and a more complex simulation model.

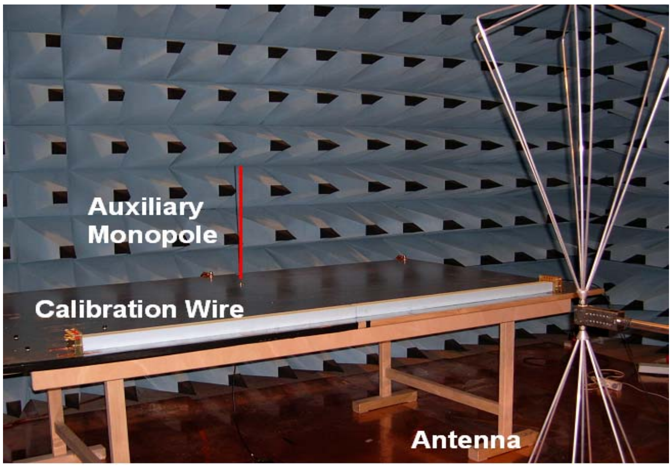

Figure 4. Setup with receiving antennas and calibration wire

Figure 4 shows the setup for the calibration measurement to determine the transfer function for the biconical antenna in vertical polarization. The networkanalyzer (ENA5070) is placed behind the structure to measure the needed scattering parameters.

V. Workflow for the Model-Generation

The basis for describing the system is represented through scattering parameters. They allow to describe the electrical behavior of the harness as well as to qualify the transfer function to the antennas. The scattering parameters can be transferred to network models via the vector fitting process, described in [6]. Vector fitting is not an easy task and may not be successful in every case. Especially if the source data are not passive, it is difficult to obtain an accurate, stable and passive network model. Post analysis is carried out within a network simulation, like shown in figure 7.

The general workflow can be split into three tasks:

A. Harness Simulation with Auxiliary Monopole

Before the radiation of the models can be considered, it is important that the simulated electrical parameters of the harness and the radiation to the auxiliary monopole are within acceptable deviations. The simulation is hereby reduced to the harness setup, the auxiliary monopole and a perfect electronic conductor plane. Due to the reduced mesh cells, which described the measurement environment and the antenna, the simulation can be speed up by a factor 500, compared to the complete simulation as shown in figure 1. If we compare figure 1 with figure 5, we can realize the amount of reduced mesh triangles. They are reduced approximately from 50,000 to 200.

As an example, the input reflection parameters out of simulation and measurement for a double wire assembly and the auxiliary monopole are compared in figure 6.

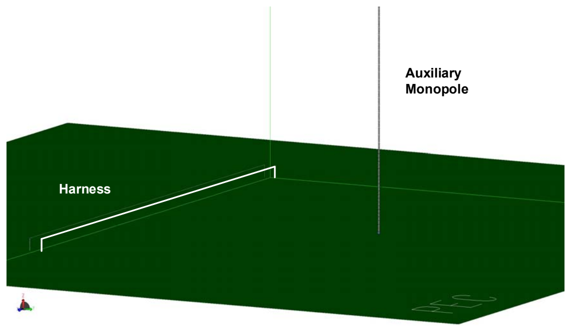

Figure 5. Simplified simulation with auxiliary monopole

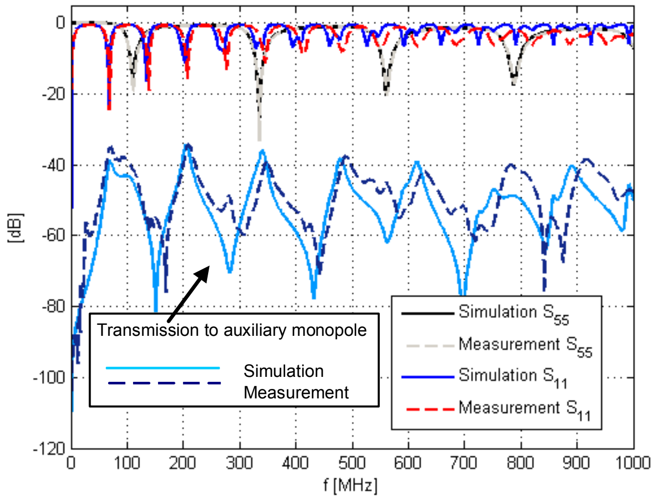

Figure 6. Double wire with auxiliary monopole structure

Simulation and measurement data show a very good accordance for the input reflection of the auxiliary monopole S_{55} in figure 6. The input reflection coefficient S_{11} of the double wire, shows good agreement to the measured data up to 500 MHz. Beyond 500 MHz, the unknown material parameters of the harness (tanδ and ε_r) lead to a frequency shift of the resonance peaks. Normally, the material parameters of the coating are unknown and more significantly temperature as well as frequency dependent. Thus, a frequency shift of the resonance peaks has to be accepted, if the material parameters of the wires are not known in detail. A frequency shift as well as deviations up to 10 dB can be seen for the transmission value to the monopole. Even a full 3D simulation of the complete setup with the conducting reference table will not generate more accurate values. The deviations result in small variations within the harness assembly compared to the simulation model and are for real harness setups hardly avoidable.

With the verified scattering parameter result out of the simulation, functional network simulation models can be created with the help of the vector fitting process. Figure 7 shows the simulation setup with the harness model and the auxiliary monopole. As within the real measurement, the monopole is terminated with 50 Ohm. Occurring radiation can now be easily predicted with the connection of the monopole. The source box in figure 7 represents an arbitrary voltage source, gained out of additional PCB simulations or measurements. The load box describes an application connected to the harness.

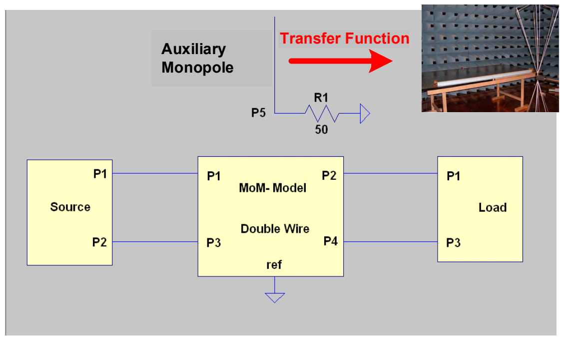

Figure 7. Network simulation model, inculuding the harness model, load / source box and the auxiliary monopole

B. *Calibration Measurement*

After the simplified simulation of the harness, the calibration measurements with the setup as shown in figure 4 are carried out. Even though the frequency range of the antennas have to be considered, all measurements are carried out over the whole frequency range form 0.3 to 1000 MHz whereas the lower frequency is limited through the used network analyzer.

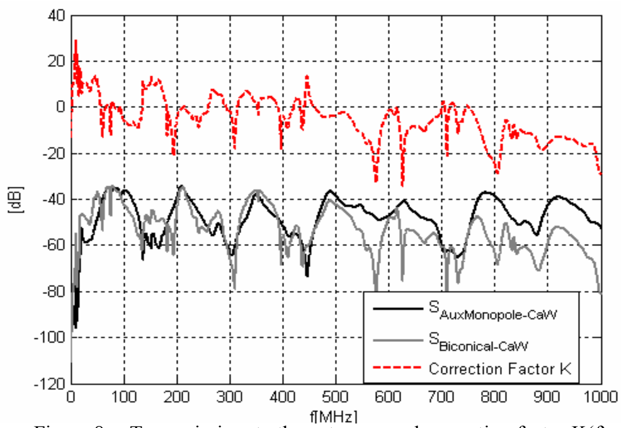

Figure 8. Transmission to the antennas and correction factor K(f)

Figure 8 shows the transmission coefficients from the calibration wire to the auxiliary monopole ($S_{AuxMonopole\text{-}CaW}$) and from the calibration wire to the biconical antenna ($S_{Biconical\text{-}CaW}$). Equation 1 leads to the correction factor K(f). With the correction factor and the simplified simulation model, it is now possible to calculate the radiation directly within a network simulation.

C. *Optional: Check predicted Radiation with Measurement*

To check the measured correction factor, one optional additional measurement can show the accuracy of the procedure. For this step, the transmission signals from one or more ports of the harness to the biconical antenna and the auxiliary monopole are measured with a networkanalyzer. The calculated transmission to the biconical antenna with the help of the transfer function can now be compared with the measured transmission.

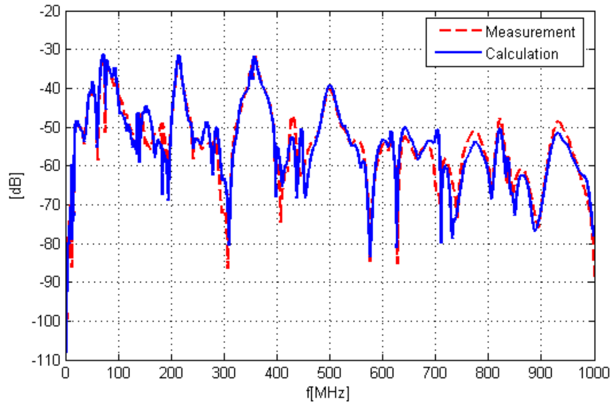

Figure 9. Measured and predicted transmission to the antenna

A double wire is placed at the previous position of the calibration wire, and the transmission of the harness to the antenna is measured. Figure 9 shows the measured and predicted transmission to the biconical antenna. The maximum deviation is lower than 5 dB over the whole frequency range. The predicted values are received out of the transmission form the harness to the auxiliary monopole and the transfer function K(f).

VI. EXAMPLE FOR A COMPLEX HARNESS STRUCTURE

To test the calibration factor of the biconical antenna for a more complex structure, a ten wire harness was chosen to compare the predicted and measured transmission to the biconical antenna in vertical polarization.

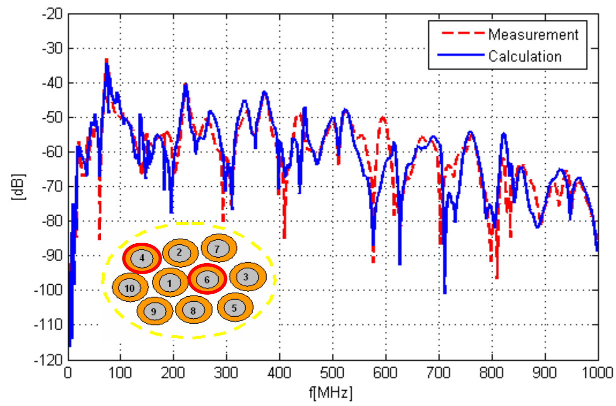

Figure 10. Ten wire harness with differential excitation (Wire 4 and 6)

Two wires of the harness are excited with a differential signal over the frequency range. A power splitter is employed to generate the differential signal at the input of the wires 4 and 6. The measured transmission to the auxiliary monopole is translated with the correction factor out of figure 8 and compared with the measured transmission to the antenna. As seen in figure 10, the deviation between the measured and predicted data is mainly less 10 dB and within acceptable ranges.

VII. ERROR ESTIMATION

The process to estimate the radiated emission with the correction factor shows low deviations compared to the measurement results. Errors occur primarily due to the limited resolution of the transmission data during the calibration measurement at resonance peaks of the calibration wire or the auxiliary monopole. However, the general error of the correction factor is mainly less than 10 dB. One possible error source is the asymmetry of the harness structure in respect to the monopole and the antenna due to the placement of the auxiliary monopole behind the harness. However, a high number of wires as well as the statistical placement of the wires within the bundle is going to decrease the error resulting out of the asymmetry. The main limiting factor of the process is given through the simulation of the harness and the transmission to the auxiliary monopole. Even a 3D simulation can not build up the cable harness in detail. Small deviations within the bundle and reallocations of single wires within the bundle can show a high impact on the radiation result, especially if the conductors are not uniform placed over the whole length. Only a worst case analysis of the radiated emission will show the maximum radiation. Nevertheless, it is possible to simplify the calculation of the radiated emission with the help of the correction factor K.

VIII. CONCLUSIONS

With the help of calibration measurements it is possible to estimate the radiated emission of arbitrary cable harnesses with simplified simulations. The model generation process is thus much faster and the surrounding environment of the setup is considered by the model. For every antenna setup at least one calibration measurement is necessary. The procedure is shown for vertical polarized antennas for which an auxiliary monopole was used. The whole process can also be expanded to horizontal antenna structures, whereas the auxiliary monopole has to be replaced by an auxiliary dipole, to cover the horizontal radiated field of the harness.

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