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Prediction of Radiated Emissions of Automotive Electronics Early in the Design Phase based on Automotive Component Level Testing

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Abstract: A method of predicting radiated emissions levels of automotive component level testing in the early design phase of an automotive electronics from a cable harness is presented. Instead of the time consuming and inaccurate common-mode current measurements on a cable harness with a radio frequency (RF) current probe, this paper proposes a novel common-mode current distribution prediction on a cable harness with the multi conductor transmission line model from imported boundary line currents or voltages from an electromagnetic (EM) simulator taking into the consideration a printed circuit board (PCB) layout and components, connectors, 2 D model of cable harness, cable harness loads etc. Radiated emissions levels are calculated from predicted common-mode current distribution on cable harness. This paper uses a component level CISPR25 cable harness layout for radiated emissions levels prediction. A radiated emissions prediction model enables an engineer to evaluate radiated emissions levels in the early design phase, when the product is still in the design phase prior to the first available prototype. As a result, radiated emissions levels can be optimised and lower cost solution can be obtained. This approach lowers the overall cost and time needed for automotive component design. The model substitutes a 3D model of cable harness above the ground plane in EM simulator and is thus much faster and uses less resources with same or even better prediction accuracy. The proposed method is validated in two absorber lined shielded enclosures (ALSE) both with an accreditation according to ISO/IEC 17025. The differences between prediction and measurements in both ALSE are explained.

Keywords: cable harness; CISPR25; common-mode current; EMC; radiated emissions

Ocena nivojev sevalnih emisij avtomobilske elektronike v zgodnji fazi njenega razvoja na podlagi testiranja avtomobilskih komponent

Izvleček: Predstavljena je metoda za oceno nivojev sevalnih emisij ožičenja avtomobilske elektronike na podlagi testiranja avtomobilskih komponent v zgodnji fazi razvoja. Namesto časovno potratnega in netočnega merjenja porazdelitve sofaznega toka na ožičenju z uporabo radio frekvenčne (RF) tokovne sonde, predlagamo metodo za oceno porazdelitve sofaznega toka na ožičenju z uporabo teorije več vodniških prenosnih linij in uvoženih robnih linijskih tokov ali napetosti iz elektromagnetnega (EM) simulatorja z vključenimi vplivi tiskanega vezja in njegovih gradnikov, priključkov, 2D modela ožičenja, bremen ožičenja itd. Nivoji sevalnih emisij so izračunani iz ocene porazdelitve sofaznega toka na ožičenju. Model za oceno nivojev sevalnih emisij je zgrajen na podlagi merilne postavitve ožičenja avtomobilske komponente iz standarda CISPR25. Model omogoča inženirjem oceno nivojev sevalnih emisij v zgodnji fazi razvoja, ko prototipi elektronike niso še na voljo. Na podlagi rezultatov je mogoča optimizacija nivojev sevalnih emisij in doseg najcenejšega dizajna elektronike. Takšen pristop omogoča nižje stroške in manj vloženega časa za načrtovanje elektromagnetno združljive avtomobilske elektronike. Predlagani model je hitrejši, potrebuje manj resursov z enako ali boljšo točnostjo kot 3D model ožičenja nad prevodno ploščo v EM simulatorju. Predlagani model smo preverili v dveh pol neodbojnih sobah, katere so akreditirane po standardu ISO/IEC 17025. Razlike med oceno in meritvami v obeh pol neodbojnih sobah smo pojasnili.

Ključne besede: ožičenje; CISPR25; sofazni tok; EMC; sevalne emisije

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1 Introduction

An electronic device has to be designed according to electrical, thermal, mechanical, functional and safety requirements. An automotive electronic device has to withstand extreme temperature conditions, temperature shocks, humidity, chemicals, mechanical shocks etc. In spite of high requirements the final product has to be inexpensive, reliable, safe and with low power consumption. The final product also has to pass the component level testing for electromagnetic compatibility (EMC). One among several EMC component level tests is also the radiated emissions measurement using antennas in an absorber lined shielded enclosure (ALSE) according to the standard CISPR 25 [1], which specifies the limits and methods of measurement for the protection of vehicles on-board receivers. In order for the product to pass the radiated emissions testing, the measured radiated emissions levels have to be below the automotive OEM specified limits in the frequency range from 150 kHz to a few GHz. Measuring radiated emissions only on the final product is risky and expensive, since about 90% of the products fail on the first radiated emissions measurements. Radiated emissions measurements conducted in the early design phase, before the testing phase, enable the designer to implement measures to reduce radiated emissions more easily, with a lower impact on the overall product cost.

Automotive OEM's specify the strictest (lowest) limit lines for radiated emissions in a frequency range from 30 MHz up to 500 MHz. The main reason for automotive OEM's high requirements for low levels of radiated emissions in this frequency range is to keep the receivers communication in these bands (e.g. 2m TAXI band, FM radio, etc.) interference-free from vehicle on-board electronics.

In the frequency range 30 MHz – 500 MHz printed circuit board (PCB) traces are small compared to the wavelength and cannot radiate efficiently. A cable harness length comparable to the electromagnetic field wavelength in a free space radiates efficiently. Common-mode currents on a cable harness have already been proven to cause the highest radiated emissions [2].

Various methods for predicting the radiated emissions from a cable harness carrying common-mode currents were already presented in [3–6]. The goal of the methods was to measure the common-mode current distribution on a cable harness in the laboratory, and to predict the radiated emissions from the measured common-mode currents. Using these methods, radiated emissions measurements in an expensive ALSE are not needed in the design phase.

The approach presented in [3] predicts the radiated emissions using multiple transfer functions, which relates the measured common-mode current distribution on a cable harness and the measured radiated emissions with an antenna. The approach takes into consideration the effect of an ALSE, test setup and an antenna on levels of radiated emissions. The calculation is only valid for an ALSE and an antenna used in the paper in frequency range from 30 MHz to 125 MHz.

The method presented in [4] specified in CISPR 25, is commonly used for emission measurements. Components or modules are required to be connected with a test cable bundle for evaluating radiated emissions. The radiation is often mainly dominated by the common mode current along the cable bundle. In order to predict radiated emissions from setups according to ALSE method, without using a large anechoic chamber, this paper presents an alternative and innovative method. The presented approach determines radiated fields from a cable bundle without phase information. It is only based on the amplitude of common mode current from phaseless measurements using a RF current probe. Firstly, radiation model of a cable bundle is simplified to a single equivalent transmission line (TL predicts radiated emissions by measuring the common-mode currents distribution on a cable harness. Common-mode current amplitude is measured along the cable harness with an RF current probe. The common-mode current phase is calculated from the measured common-mode amplitude with phase retrieval algorithm. Radiated emissions are calculated by splitting the cable harness to infinitesimal Hertzian dipoles and summing the contribution of all Hertzian dipoles at the antenna tip. The effect of the ground plane on levels of radiated emissions is taken into account by using the mirror method of Hertzian dipoles. The proposed method suffers from errors in the phase retrieval algorithm, especially in the lower frequency range. The same authors improved the calculation of the radiated emissions from the common-mode current distribution in [5]. A major improvement is related to the levels of radiated emissions in horizontal antenna polarization by implementing a method of calculating the current distribution on the surface of the ground plane. In this way the effect of the finite size of the ground plane on the levels of radiated emissions is considered. The same authors again improved the calculation of radiated emissions in [6]. The authors propose current scanning in the time domain to improve the phase retrieval algorithm in the lower frequency range. In addition, a prediction of radiated emissions is also improved by considering the ALSE and antenna effects with a calibration procedure.

The disadvantage of all the previous methods is the need for common-mode current distribution measurement, which can be time consuming and requires additional equipment for RF current probe positioning. An RF current probe also adds insertion impedance to the cable harness common-mode impedance and thus influences measurement results [7]. The RF current probe positioning on the cable harness affects the accuracy of common-mode current distribution. The method also cannot be used in the early design phase, when a prototype is not yet available.

The common error of the presented papers is also in modelling the straight cable harness 10 cm from the ground plane front edge, without the 90 degrees bends, which is not equal to the cable harness layout as specified in the CISPR25 [1]. This cable layout [3–6], which is not according to the standard, is illustrated in fig. 1.

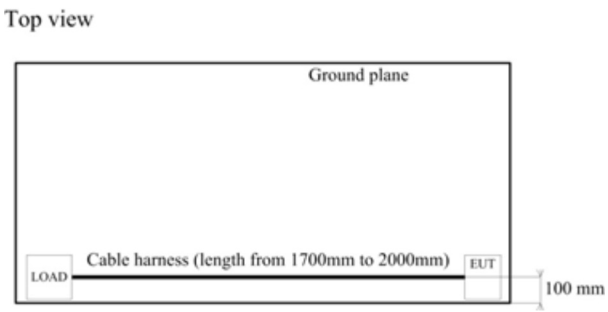

Figure 1: Straight cable harness located 100 mm from the front edge of the ground plane.

It is well known that a cable harness layout has an impact on radiated emissions levels.

This paper presents a method of predicting radiated emissions levels of automotive component level testing in the early design phase of a product. The cable harness currents and voltages are imported from an EM simulator taking into the consideration a PCB layout and components, cable harness connector, 2D model of the cable harness, cable harness loads (artificial load for power supply lines, load simulators for data/signal lines). The model predicts a common-mode current distribution on a cable harness using the multi conductor transmission lines (MTL) method and boundary line currents or voltages imported from an EM simulator. The cable harness is divided into infinitesimal current elements (Hertzian dipoles), which represent a radiating structure. Vertical grounding connections are also added to the radiating structure. The cable harness layout, as specified in the CISPR25 [1], is modelled in this paper.

Sections of the rest of the paper are organized in the following manner. Section II introduces the CISPR25 test setup as the basis for the radiated emissions prediction model in section III. Prediction of the common-mode current distribution on the cable harness is presented in section IV. Proposed radiated emissions prediction model is validated in section V. Simulation results are compared with the radiated emissions and common-mode current measurements in two semi-anechoic chambers. The conclusion is presented in Section VI.

2 CISPR25 test setup

Fig. 2 shows a test setup for automotive radiated emissions measurements according to CISPR25 [1] in the lowest frequency range 150 kHz – 30 MHz using a rod antenna. Fig. 3 also shows the test setup for automotive radiated emissions measurement according to CISPR25 [1], but in the frequency range of 30 MHz – 1000 MHz using a logarithmic antenna. The difference between both setups is only in the type of the antenna. Radiated emissions are measured with a rod antenna only in vertical polarization, while with a logarithmic antenna measurements are done with both horizontal and vertical antenna polarization.

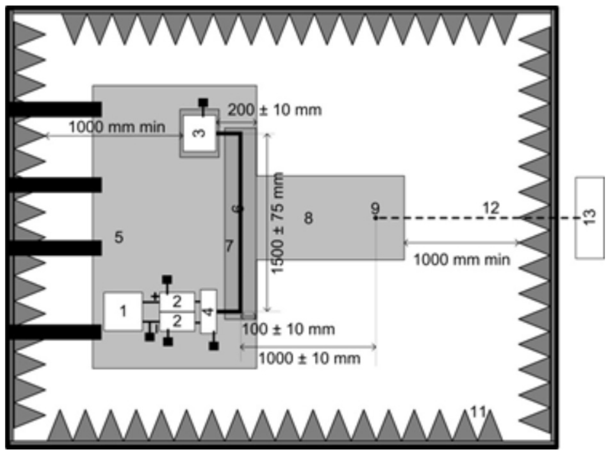

Figure 2: Test setup for radiated emissions measurements from an automotive component with an attached cable harness according to CISPR25 [1] in the frequency range of 150 kHz – 30 MHz using a rod antenna.

Test setup according to CISPR25 [1] has to be known down to details in order to be able to build a good simulation model for predicting radiated emissions levels in automotive component level testing.

3 Radiated emissions prediction model

The radiated emissions prediction model consists of a large number of Hertzian dipoles, which represents the

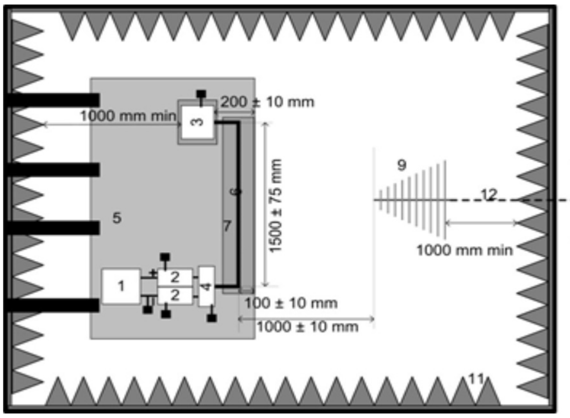

Figure 3: Test setup for radiated emissions measurements from an automotive component with an attached cable harness according to CISPR25 [1] in the frequency range of 30 MHz – 1000 MHz using a logarithmic antenna.

structures, where the currents are flowing. A Hertzian dipole is a current element with a length small enough to have a constant current amplitude along its length at the highest frequency of interest. The Hertzian dipole radiated fields (electric and magnetic fields) equations in a Cartesian coordinate system in the frequency domain are used, which enables a simple way of summing the radiated fields in a specific point in space.

Fig. 4 shows a simplified geometry of the cable harness with the vertical ground connections to the ground plane and the ground plane created according to CISPR25 [1] that enables calculation of radiated emissions in the observation point – at the tip of the antenna T_{ANT}.

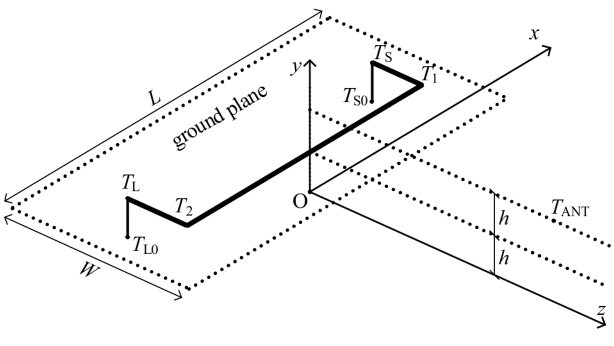

Figure 4: Simplified CISPR25 geometry used for radiated emissions calculations

The cable harness has a total length of l, which has to be smaller than 2000 mm according to CISPR25 [1], but according to some automotive OEM's requirements the length of the cable harness has to be in a range from 1700 mm to 2000 mm. The ground plane has a defined width W and length L. Cable harness is routed from the front side of the equipment under test (EUT) located at point T_S to load simulators located at point T_L. Detailed cable harness positioning is presented below.

The point T_S = (750, 50, -100) mm represents the EUT front side, where the cable harness starts. The point T_{S0} = (750, 0, -100) mm represents the nearest EUT connection to the ground plane, the location where the common-mode current returns back to the EUT. The cable harness first bends at the point T_1 = (750, 50, 0) mm at preferable 90 degrees according to the standard [1]. The cable harness is laid 100 mm from the front edge of the ground plane at 50 mm height above the ground plane in a total length of 1500 mm from the point T_1 to the point T_2 = (-750, 50, 0) mm. This is also the point where the second bend of the cable harness is done. The rest of the cable harness length (l - 1600) is then connected to the load simulators and artificial networks (ANs), at point T_L = (-750, 50, - (l – 1600)) mm. The grounding connection from AN or a load simulator is modelled between points T_L and T_{L0} = (-750, 0 - (l - 1600)) mm. Point T_{L0} is the point, where common-mode current is injected from the cable harness to the ground plane.

The cable harness is split into small segments, which are modelled as Hertzian dipoles. The Hertzian dipole current is equal to the cable harness common-mode current, where the Hertzian dipole is located on the cable harness. Vertical grounding connections at EUT from the point T_{S0} and T_S and at load simulator or AN side from points T_{L0} and T_L are also modelled as the Hertzian dipole and their current is equal to the cable harness current at each vertical grounding connection.

In order to be able to use the radiated fields' equations at an arbitrary point along the cable harness, a Cartesian coordinate system rotation has to be performed. Rotation of each Hertzian dipole Cartesian coordinates must be performed so that the direction of the Hertzian dipole is directed in the direction of the transformed z axis. In the transformed Cartesian system the radiated fields are calculated. The calculated radiated fields have to be again transformed back to the original Cartesian coordinate system, where contributions from all Hertzian dipoles are added together.

The ground plane effects to the radiated emissions can be modelled by implementing the mirror theory to the cable harness. This is done at a lower frequency range 150 kHz – 30 MHz, where the mirror theory perfectly predicts radiated emissions levels. Fig. 5 shows workflow to calculate the radiated emissions in vertical antenna polarization in the frequency range 150 kHz – 30 MHz using mirror theory.

However, mirror theory poorly predicts vertical and horizontal radiated emissions levels in the frequency range of 30 MHz – 1000 MHz, therefore radiated emissions are modelled by implementing the PO-model as was already presented in [6].

The PO model calculates the induced current (return common-mode currents) on the surface of the ground plane, due to the common-mode currents on the cable harness and mirrored cable harness [6]. The calculation is done by slicing the ground plane into small rectangular surfaces, whose dimensions are sufficiently small compared to the wavelength at the highest frequency of interest. Contribution of the current distribution on the ground plane to radiated emissions is modelled by a Hertzian dipole in each cell in x and z directions [5].

The radiated emissions levels are predicted with the highest accuracy by summing the radiated electric field due to the common-mode current in the cable harness and vertical ground connections as well as the currents on the surface of the ground plane. Fig. 6 shows workflow to calculate the radiated emissions in horizontal and vertical antenna polarization in the frequency range 30 MHz – 1000 MHz using PO model.

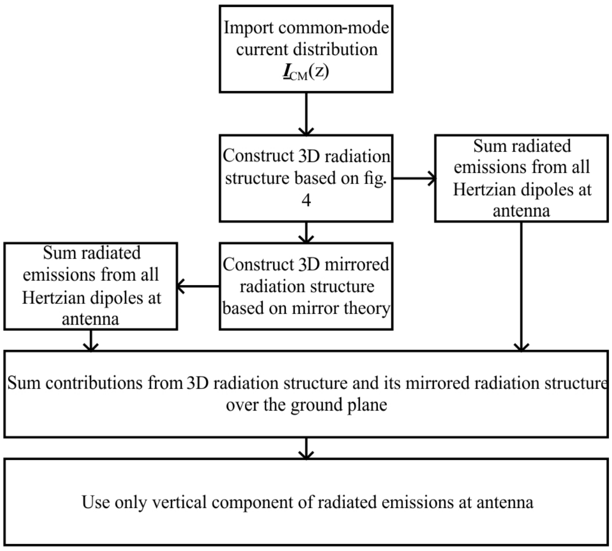

Figure 5: Workflow to calculate the radiated emissions in the frequency range 150 kHz – 30 MHz using only mirror theory.

4 Common-mode current distribution on the cable harness

Common-mode current distribution on a cable harness is predicted using the multi conductor transmission lines (MTL) model in the frequency domain [8].

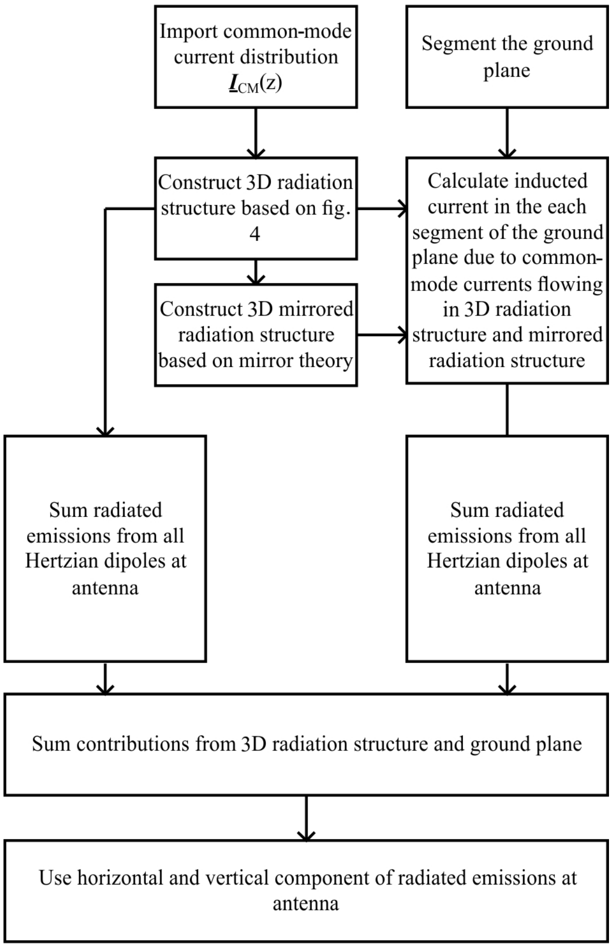

Figure 6: Workflow to calculate the radiated emissions in the frequency range 30 MHz – 1000 MHz using PO method.

Fig. 7 shows the definition of differential-mode currents (the ones with return path on the reference conductor in a cable harness) and common-mode currents (the ones with return path on the reference ground plane). This definition enables the calculation of common-mode current distribution along the cable harness with the MTL.

The height of a cable harness above the ground plane (50 mm in this case) is the limiting property for the highest frequency for which the transmission line model of the common-mode current distribution is still valid. The highest frequency for the transmission line model is around 500 MHz, where the distance of the cable harness above the ground plane violates the rule that the distance should be smaller than the wavelength, e.g. smaller than λ/10.

Transmission lines properties are modelled by the parameters defined per unit length: resistance, inductance, capacitance and conductance (RLGC). MTL are modelled as lossy. The transmission line parameters

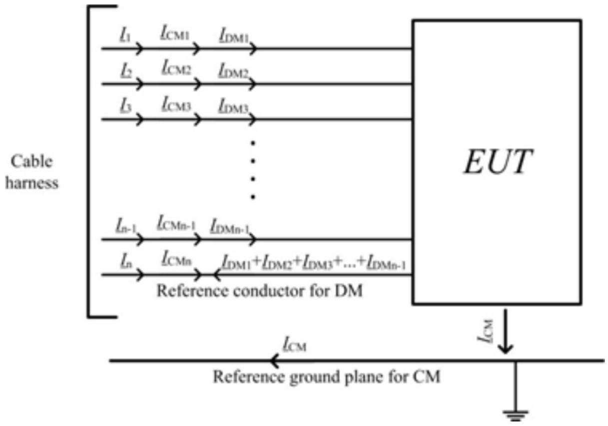

Figure 7: Definition of differential-mode and common-mode cable harness currents from cable harness line currents.

are obtained from a 2D model of a cable harness in an EM simulator.

The voltages $\underline{\mathbf{V}}(z)$ and currents $\underline{\mathbf{I}}(z)$ on each line of the multi conductor transmission line can be calculated by decoupling the coupled transmission lines by modal analysis [8]. The line currents $\underline{\mathbf{I}}(z)$ and voltages $\underline{\mathbf{V}}(z)$ at various distances from the source z are transformed to the modal currents $\underline{\mathbf{I}}_m(z)$ and voltages $\underline{\mathbf{V}}_m(z)$ on MTL. The line currents and voltages at various distances from the source can be calculated [8]

$$\underline{\mathbf{I}}(z)=\underline{\mathbf{T}}_I\underline{\mathbf{I}}_m(z)=\underline{\mathbf{T}}_I\left(\mathbf{e}^{-\underline{\gamma}_m z}\underline{\mathbf{I}}_m^{+}-\mathbf{e}^{\underline{\gamma}_m z}\underline{\mathbf{I}}_m^{-}\right) \tag{1}$$

$$\underline{\mathbf{V}}(z)=\underline{\mathbf{T}}_V\underline{\mathbf{V}}_m(z)=\underline{\mathbf{Z}}_0\underline{\mathbf{T}}_I\left(\mathbf{e}^{-\underline{\gamma}_m z}\underline{\mathbf{I}}_m^{+}+\mathbf{e}^{\underline{\gamma}_m z}\underline{\mathbf{I}}_m^{-}\right) \tag{2}$$

where $\underline{\mathbf{T}}_V$ is the voltage transformation matrix and $\underline{\mathbf{T}}_I$ is the current transformation matrix, $\underline{\mathbf{Z}}_0$ is the line characteristics impedance matrix and $\underline{\gamma}_m$ is the diagonal modal propagation constant matrix. The vectors $\underline{\mathbf{I}}_m^{+}$ and $\underline{\mathbf{I}}_m^{-}$ representing the constant values are defined by incorporating the boundary conditions at the beginning (source side – EUT side) $\underline{\mathbf{I}}(0)$ or $\underline{\mathbf{V}}(0)$ and at the end (load side) $\underline{\mathbf{I}}(L)$ or $\underline{\mathbf{V}}(L)$ of the multi conductor transmission line. The boundary conditions are obtained by constructing the whole simulation model consisting of: PCB layout and components, connectors, housing, a 2 D model of a cable harness and cable harness loads (artificial load for power lines and load simulator for data/signal lines) in an EM simulation software. The boundary voltages or currents are exported to the common-mode current distribution prediction model. The boundary conditions written for the currents on lines are

$$\underline{\mathbf{I}}(0)=\underline{\mathbf{T}}_I\underline{\mathbf{I}}_m(0)=\underline{\mathbf{T}}_I\left(\underline{\mathbf{I}}_m^{+}-\underline{\mathbf{I}}_m^{-}\right) \tag{3}$$

$$\underline{\mathbf{I}}(L)=\underline{\mathbf{T}}_I\underline{\mathbf{I}}_m(L)=\underline{\mathbf{T}}_I\left(\mathbf{e}^{-\underline{\gamma}_m L}\underline{\mathbf{I}}_m^{+}-\mathbf{e}^{\underline{\gamma}_m L}\underline{\mathbf{I}}_m^{-}\right) \tag{4}$$

and for the voltages on lines

$$\underline{\mathbf{V}}(0)=\underline{\mathbf{Z}}_0\underline{\mathbf{T}}_I\left(\underline{\mathbf{I}}_m^{+}+\underline{\mathbf{I}}_m^{-}\right) \tag{5}$$

$$\underline{\mathbf{V}}(L)=\underline{\mathbf{Z}}_0\underline{\mathbf{T}}_I\left(\mathbf{e}^{-\underline{\gamma}_m L}\underline{\mathbf{I}}_m^{+}+\mathbf{e}^{\underline{\gamma}_m L}\underline{\mathbf{I}}_m^{-}\right) \tag{6}$$

Using the exported values from an EM simulator software the vector $\underline{\mathbf{I}}_m^{+}$ and $\underline{\mathbf{I}}_m^{-}$ representing the constant values can be easily calculated from the boundary currents of the MTL

$$\underline{\mathbf{I}}_m^{+}=\underline{\mathbf{T}}_I^{-1}\underline{\mathbf{I}}(0)+\underline{\mathbf{I}}_m^{-} \tag{7}$$

$$\underline{\mathbf{I}}_m^{-}=\left(\mathbf{e}^{-\underline{\gamma}_m L}-e^{\underline{\gamma}_m L}\right)^{-1}\left(\underline{\mathbf{T}}_I^{-1}\underline{\mathbf{I}}(L)-e^{-\underline{\gamma}_m L}\underline{\mathbf{T}}_I^{-1}\underline{\mathbf{I}}(0)\right) \tag{8}$$

or from the boundary voltages of the MTL

$$\underline{\mathbf{I}}_m^{+}=\underline{\mathbf{T}}_I^{-1}\underline{\mathbf{Z}}_0^{-1}\underline{\mathbf{V}}(0)-\underline{\mathbf{I}}_m^{-} \tag{9}$$

$$\underline{\mathbf{I}}_m^{-}=\left(\mathbf{e}^{\underline{\gamma}_m L}-\mathbf{e}^{-\underline{\gamma}_m L}\right)^{-1}\begin{pmatrix}\underline{\mathbf{T}}_I^{-1}\underline{\mathbf{Z}}_0^{-1}\underline{\mathbf{V}}(L)-\\ \mathbf{e}^{-\underline{\gamma}_m L}\underline{\mathbf{T}}_I^{-1}\underline{\mathbf{Z}}_0^{-1}\underline{\mathbf{V}}(0)\end{pmatrix} \tag{10}$$

The common-mode current distribution on a cable harness according to our definition in Fig. 5 can be obtained from the calculated line currents on the MTL by summing all the line currents $\underline{I}_k(z)$ at the desired distance *z* from the source side (EUT side)

$$\underline{I}_{cm}(z)=\sum_k \underline{I}_k(z) \tag{11}$$

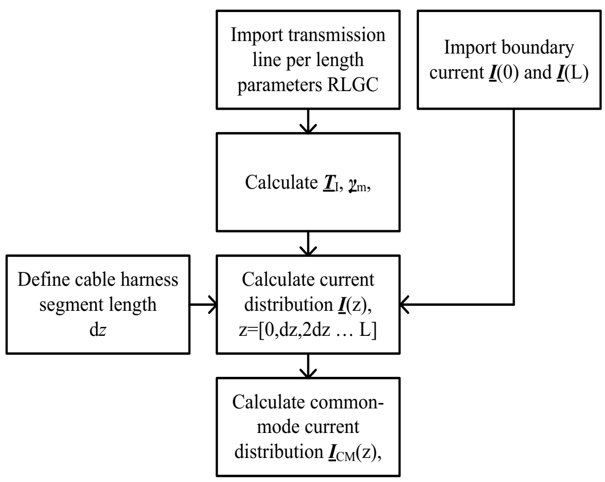

Figure 8: Workflow to calculate the common-mode current distribution on cable harness in frequency range 150 kHz – 1000 MHz using MTL model.

Fig. 8 shows the workflow to calculate the common-mode current distribution on cable harness in the frequency range 150 kHz – 1000 MHz using MTL model.

5 Validation

The proposed prediction models of the common-mode currents on a cable harness and automotive component radiated emissions testing are validated by measurements in two ALSEs with the accreditation according to ISO/IEC 17025 [9]. Firstly, the validation is done in the EMC Laboratory at MAHLE Letrika d.o.o., and secondly the validation is repeated in the EMC Laboratory at SIQ Laboratory for Electromagnetics. Two validations in separate absorber lined shielded enclosures are performed to show the high level of measurement inaccuracy and uncertainty in radiated emissions measurements according to CISPR25 [1].

Fig. 9 shows the simulation model we constructed in an EM simulator to predict the common-mode current distribution on a cable harness. Only common-mode voltage source excitation was used for the cable harness.

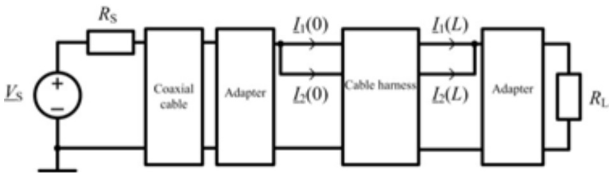

Figure 9: Simulation model used for predicting the common-mode current distribution on cable harness constructed in an EM simulator.

The EMI receiver's tracking generator, represented by the voltage source $\underline{V}_S$ and the equivalent generator resistance R_S, is used to excite the cable harness built from two parallel conductors of the type FLRY-B with a 0.75 mm^2 cross section area and which are two meters long. The tracking generator output power is set to -20 dBm during measurements. An adapter with a female N connector had to be mounted on each side of the cable harness to enable cable harness termination and excitation. The adapter is modelled in an EM simulator to include all parasitics. The cable harness is modelled as 2 D structure in an EM simulator. The coaxial cable is also modelled in an EM simulator to include attenuation and a velocity factor. The load side adapter of the cable harness is terminated with a 50 Ohm load. A coaxial cable ECOFLEX15 14 meters long connected the tracking generator to the cable harness source side adapter.

Time required to build a complete model in EM simulator is about 4 h in 4000 frequency points. The time required to simulate the complete model is about 40 minutes in 12704 frequency points with interpolation. Common-mode current distribution on cable harness and radiated emissions simulation are finished in 5 minutes. We are running simulations on system with the following specifications: 2 XEON processors eight core, sixteen threads, E5-2680 running at 2.7 GHz clock with 128 GB ram on a 64 bit operating system.

5.1 Common-mode current distribution on cable harness

Figs. 10–12 show the predicted and measured common-mode currents at three locations on a cable harness. The measurements are done at MAHLE Letrika d.o.o. and at SIQ using Fischer F-52 RF current probe. The figures show minor deviations between the predicted and measured common-mode currents at frequencies of up to 400 MHz at MAHLE Letrika d.o.o. Higher deviations are seen between measurements at MAHLE Letrika d.o.o. and SIQ. The reason for the deviation is the tracking generator's typical output level deviation of 1.9 dB in the frequency range 150kHz – 1 GHz.

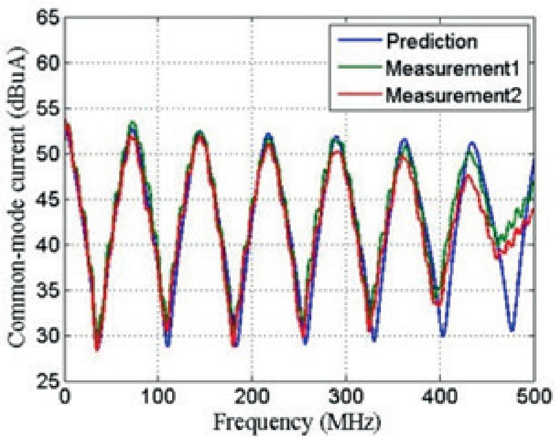

Figure 10: Comparison of the predicted and measured common-mode currents at the source side of the cable harness at MAHLE Letrika d.o.o. (Measurement1) and at SIQ (Measurement2).

The tracking generator output level was modelled with a nominal level (-20 dBm) and the output impedance as 50 Ω resistance, without taking into consideration the output port VSWR. The cable harness termination 50 Ω load was also modelled as a 50 Ω resistance, without taking into account the load VSWR. Above the frequency of 450 MHz the cable harness cannot be modelled anymore with the MTL model. Higher modes of propagation besides the TEM mode exist and the current dis-

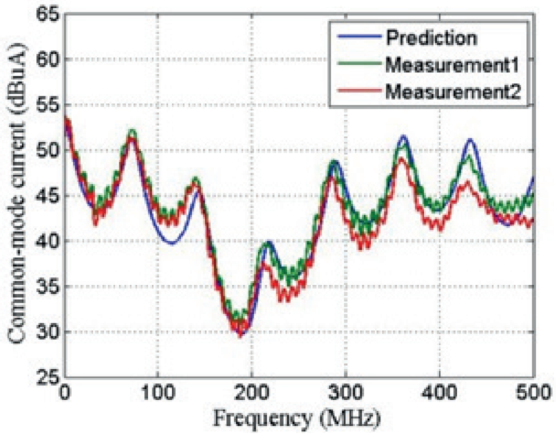

Figure 11: Comparison of the predicted and measured common-mode currents at 167 cm along the cable harness from the source side at MAHLE Letrika d.o.o. (Measurement1) and at SIQ (Measurement2).

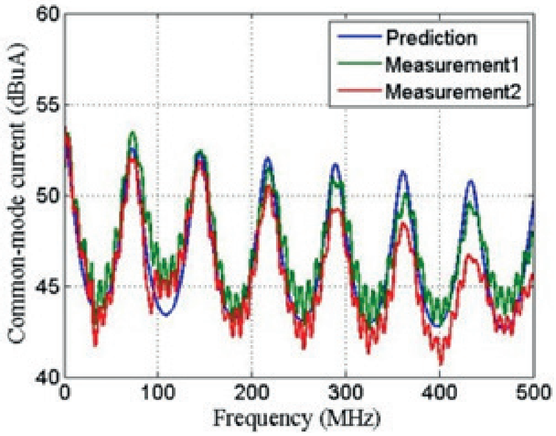

Figure 12: Comparison of the predicted and measured common-mode currents at the load side of the cable harness at MAHLE Letrika d.o.o. (Measurement1) and at SIQ (Measurement2).

tribution on a cable harness can be predicted only by a full-wave model.

5.2 Radiated emissions levels from cable harness

Fig. 13 shows a comparison of the predicted radiated emissions levels and measured radiated emissions levels at MAHLE Letrika d.o.o. and SIQ in the frequency range 150 kHz – 30 MHz in vertical antenna polarization. The ground plane height above the chamber floor was 95 cm at MAHLE Letrika d.o.o., 84 cm at SIQ and 7 cm at SIQ when the ground plane was lowered closer to the chamber floor. The deviation occurring at higher frequencies is due to resonances occurring between the ground plane and chamber floor via grounding of the ground plane to the chamber floor [6]. We have confirmed these findings by positioning the ground plane closer to the chamber floor at SIQ (Fig. 10, Measurement3). The deviation between the Measurement3 and the prediction is minimal and is within ± 2 dB. We can expect deviations up to 20 dB in radiated emissions levels between a different ALSE using the test setup according to CISPR25 [1] in the frequency range 15 MHz – 30 MHz.

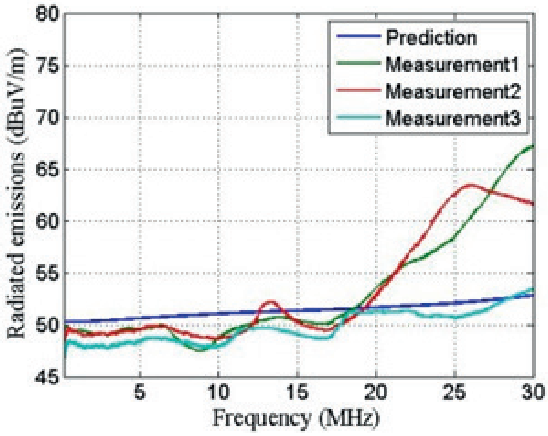

Figure. 13: Comparison of the predicted and measured radiated emissions levels at MAHLE Letrika d.o.o. (Measurement1), at SIQ (Measurement2) and additional measurement at SIQ by lowering the ground plane closer to the chamber floor (Measurement3).

Fig. 14 – 16 show the predicted and measured radiated emissions levels in the frequency range 30 MHz – 1000 MHz at MAHLE Letrika d.o.o. and at SIQ. Fig. 14 and 15 show radiated emissions levels in vertical and horizontal antenna polarization, respectively. Fig. 16 shows the maximum radiated emissions levels in both antenna polarisations.

Fig. 17 shows deviations between the predicted and measured radiated emissions levels in the frequency range 30 MHz – 1000 MHz in both antenna polarizations at MAHLE Letrika d.o.o. and SIQ. The deviations are calculated by subtracting the predicted maximum radiated emissions level in both antenna polarizations from those measured at MAHLE Letrika d.o.o. (Deviation1) and at SIQ (Deviation2).

The deviations between the prediction and measurements occur in the lower frequency range below 100 MHz due to grounding resonances, ground plane size, and ALSE resonances [10]. The ground plane used at MAHLE Letrika d.o.o. and at SIQ was not the same size. The ground plane size used in testing at MAHLE Letrika was 2.5 m long by 1.25 m wide. At SIQ the size of the ground plane was 2.2 m long by 1.2 m wide. The ground plane height used at MAHLE Letrika d.o.o. was 95 cm, while at SIQ it was 84 cm. A completely different

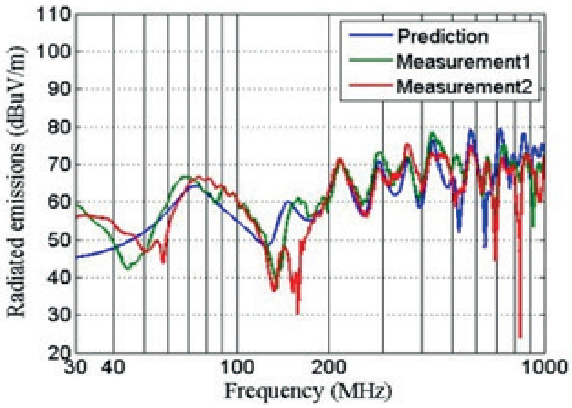

Figure 14: Comparison of the predicted and measured radiated emissions levels in the frequency range 30 MHz – 1000 MHz in vertical antenna polarization at MAHLE Letrika d.o.o. (Measurement1) and at SIQ (Measurement2).

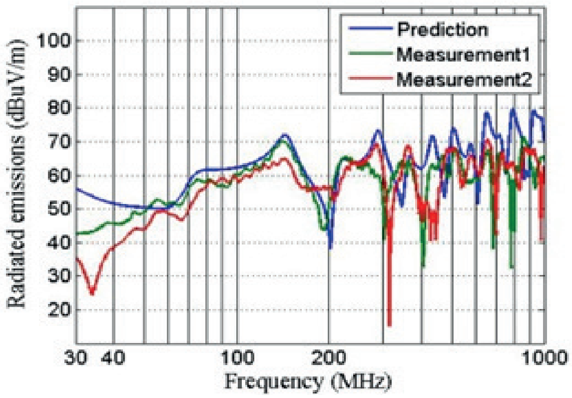

Figure 15: Comparison of the predicted and measured radiated emissions levels in the frequency range 30 MHz – 1000 MHz in horizontal antenna polarization at MAHLE Letrika d.o.o. (Measurement1) and at SIQ (Measurement2).

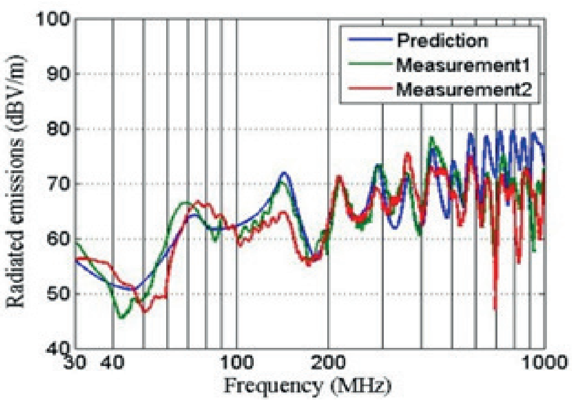

Figure 16: Comparison of predicted and measured radiated emissions levels in the frequency range 30 MHz – 1000 MHz in both antenna polarizations at MAHLE Letrika d.o.o. (Measurement1) and at SIQ (Measurement2).

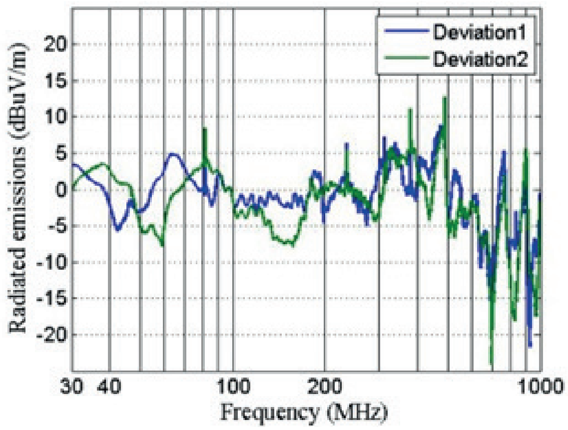

Figure 17: Deviations between the predicted and measured radiated emissions levels in the frequency range 30 MHz – 1000 MHz in both antenna polarizations at MAHLE Letrika d.o.o. (Deviation1) and at SIQ (Deviation2).

ALSE was used at MAHLE Letrika d.o.o. compared to the ALSE at SIQ. The difference is in the size of the ALSE, absorbers performances, etc. All of the presented parameters have an impact on measured radiated emissions levels in the frequency range below 100 MHz.

Additional deviations between the prediction and measurements can be seen at frequencies around 150 MHz. We believe that high sensitivity of radiated emissions levels to variance in cable harness position above ground plane can be seen in this frequency range. A small difference (in order of a few milimeters) in the distance of the cable harness from the edge of the ground plane has a high effect on radiated emissions levels around 150 MHz.

The deviations between the prediction and measurements above 450 MHz frequency are caused by an inaccurate common-mode current distribution on a cable harness using the MTL model. The cable harness height of 50mm above the ground plane limits the maximum frequency for which the MTL model is still valid. Above 500 MHz the product PCB and inside connections will also contribute to overall radiated emissions if the product housing is plastic.

Deviations up to 10 dB could be seen between the measurement at MAHLE Letrika d.o.o. and at SIQ. This means that if radiated emissions levels are measured above automotive OEM's limit lines, the source of the radiated emissions is reduced and the levels are reduced 2 – 3 dB below the automotive OEM's limit lines in the ALSE1, there is no guarantee that the product will also pass radiated emissions measurement in the ALSE2. A higher margin of about 6 dB is recommended in order to guarantee that the product will also pass radiated emissions testing in other ALSE.

6 Conclusion

A radiated emissions prediction model is developed to estimate the radiated emissions levels from a cable harness above the ground plane according to CISPR25 [1] in the frequency range 150 kHz – 1000 MHz. The dominant radiated emissions result from common-mode currents on the cable harness, currents in the ground plane and the current on vertical grounding connections. The common-mode current distribution on a cable harness is predicted with good accuracy, up to 450 MHz using the multi conductor transmission line model (MTL) and MTL boundary conditions obtained from EM simulation software, where PCB layout, component, connectors, housing, cable harness 2D model and cable harness loads are modelled by appropriate numerical methods (FEM or BEM). The effect of the ground plane on radiated emissions levels above 30 MHz is considered by calculating the current on the surface of the ground plane. The surface current is calculated using Ampere's law from the common-mode current distribution on a cable harness and mirrored common-mode current distribution over the ground plane (mirror theory). The radiated emissions from the common-mode current distribution, currents in the ground plane, and currents of the vertical grounding connections can be predicted using Hertzian dipoles for frequencies above 30 MHz. The radiated emissions levels below 30 MHz are predicted from the common-mode current distribution on the cable harness, mirrored common-mode current distribution on the mirrored cable harness over the ground plane, and the current on the vertical grounding connections.

The presented radiated emissions prediction obtained by the predicted common-mode current on a cable harness offers insight into the source of emissions of a product, and enables an engineer to reduce the radiated emissions of a product below automotive OEM's limits in the product design phase prior to the first prototype. It also reduces the need to model the CISPR25 radiated emissions test setup in a 3D EM simulator and thus reduces the calculation time and the computer resources needed. An EM simulator is needed to calculate the voltages or currents at the beginning and at the end of the cable harness, which are imported to novel common-mode current distribution prediction model. Boundary voltages or currents on cable harness are then imported into the radiated emissions prediction model, which calculates the levels of radiated emissions according to CISPR25 setup. The radiated emissions prediction model could even be integrated into an EM simulator as an option to calculate CISPR25 radiated emissions levels.

This workflow reduces the resources needed to repeat testing in an ALSE and to build numerous prototypes. It even enables a radiated emissions levels prediction in the early design phase, when the product prototype is not available for testing.

The presented method is much faster compared to other numerical methods (FEM or MOM) often used for radiated emissions evaluations of CISPR25 test setup in 3D space. It enables radiated emissions prediction in a few minutes in over ten thousand frequency points.

A validation was done with an automotive cable harness consisting of two cables, 50 Ohm termination load, and a tracking generator as a source. Our next task is to model an automotive electronic component together with the cable harness and load in an EM simulator and use the presented model to predict radiated emissions levels.

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