COUPLING OF INHOMOGENEOUS FIELDS INTO AN AUTOMOTIVE CABLE HARNESS WITH ARBITRARY TERMINATIONS

S. Frei*, R. Jobava**
*Audi AG, Germany
**Tbilisi State University, Georgia
(Principal contact: stephan.frei@audi.de)

Abstract: Electronic equipment in automobiles can be exposed to very high field strengths. The cable harness is - from the EMC point of view - the most critical part of an automobile. A direct computation of the terminal voltages of the cable harness with a 3D field solver is due to the different structure sizes of wires and car body nearly impossible. A new hybrid method based on Transmission Line (TL) theory, the Method of Moments (MoM), and circuit simulation programs was developed to calculate the coupling of inhomogeneous fields into non-uniform transmission lines, terminated with arbitrary non-linear circuits. Selected examples show the applicability of the method.

1. Introduction

Due to the increasing number of electronic systems assembled inside cars EMC plays an increasingly important role in the automotive development process. The demands in the automotive area are very high compared to the demands for standard consumer electronics. Cars are tested for proper function in modulated fields with field strength up to 120 V/m, and single systems have to withstand electrical field strength up to 200 V/m in a wide frequency range.

Furthermore cars can be a victim of transient currents and fields generated for example by an Electrostatic Discharge (ESD) or a lightning stroke. In future with the use of “brake-by-wire” or “steer-by-wire” systems the demands on the EMC will increase dramatically.

For most EMC considerations the installed electronic components can be treated as lumped element circuits, their size is often much smaller than the wavelength of the incident fields. Mainly the cable harness acts as receiving structure for the energy of an incident field. Due to the fact that the whole cable harness in upper class cars can have a total length of some 1000 meters, the size of the coupling structure is very large.

Even when the dielectric material inside a car is neglected and only the car body is assumed to influence the field propagation inside a car, the calculation of the voltages over the terminals of the wires is a very challenging task. The structure sizes differ extremely. The chassis has an extension of some meters, that has to be modeled. The wire system, that is mainly placed very close to the car body (metal plane), has diameters and distances between the wires as well as to metallic structures that can be specified in sub-millimeter range. An accurate model of such a system for numerical field calculation methods like MoM, FEM, FDTD, or TLM leads to a very large number of unknowns. The afforded memory and computational power exceeds often by far the capabilities even of super-computers.

Decomposition methods are required [1]. From the EMC point of view an automobile can be subdivided into three “sections”:

- The car body; i.e. all large metallic parts.
- The cable harness; this is the receiving structure for the fields.
- The electronic components; i.e. all terminations of the cable harness.

Based on these definitions the automotive can be decomposed and the field coupling calculation can be done. This paper presents a hybrid method based on two main steps:

1. The field that illuminates the wire system is calculated without the wire system. The field distribution within the car body can be calculated by a common 3D code. MoM is for the lower and medium frequency range (up to 500 MHz) the best choice, because it allows to model the chassis with a relative low number of elements quite accurate, as long as only the metallic parts have to be considered. Figure 1 shows an example for a car mesh and a field plot.
2. Once the fields are determined, the coupling into the wire system can be considered by an extended Transmission Line theory. The basic TL-theory is already widely used in the automotive area for the calculation of the crosstalk [2,3]. The TL-theory can be extended with forcing functions that considers the field to line coupling [4,5]. With this extended TL-theory the line termination voltages can be calculated.

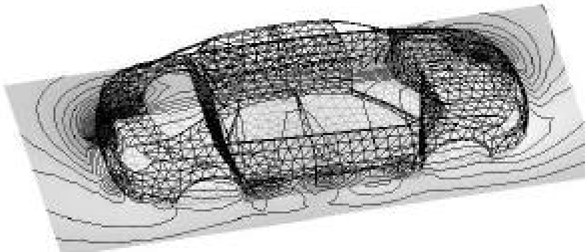

Figure 1: Contour-plot of a calculated field inside and outside of a car body

As the most problems are combined with nonlinear and active terminations, the transmission lines are non-uniform, and the fields inhomogeneous, the numerical treatment is very difficult. Only special cases could be calculated. In [6] e.g. uniform MTL (Multiconductor Transmission Lines) were calculated in the time domain with nonlinear loads, [7] expands the TL equations for non-uniform TL excited by a plane wave, in [8] a method is presented that calculates non uniform MTL in transient fields. All methods have in common that they are difficult to handle and they can almost not be combined with complex nonlinear and active terminations.

We choose a pragmatic straightforward approach that overcomes all of the mentioned problems. We modeled the field excited MTL with lumped circuits and analyzed the resulting circuits with circuit simulation techniques. This Lumped Circuits TL - (LCTL) approach was tested on different configurations and checked against other methods. The method and selected results are presented here.

2. Method

The method can be divided into steps. The single steps are shown in a flowchart (Figure 2). The more complex steps are explained in this section.

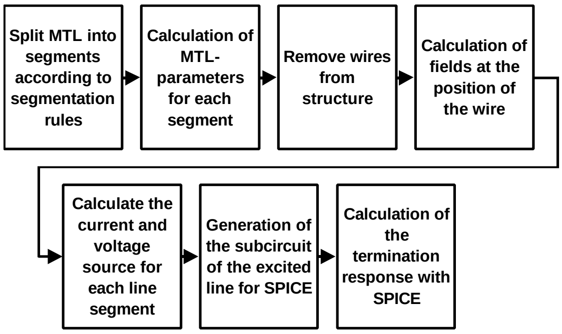

Figure 2: Flowchart for the calculation of the termination response of a field excited MTL

2.1 Segmentation of the line

In the first step the investigated TL or MTL has to be split into segments. Each segment can be approximated by an uniform TL or MTL with its parameters. The result is a cascaded series of sections of uniform lines (Figure 3).

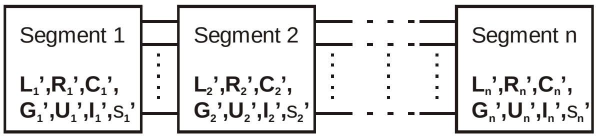

Figure 3: Dividing a TL into short segments with length s_i. Each segment is characterized by its TL-parameters

Each line segment has its own characteristic impedance matrices, forcing terms and length (Figure 3). The line lengths are assumed to be short, so each segment can be modeled with a lumped circuit. In Figure 4 an example for a short MTL-segment modeled as a T-circuit is shown.

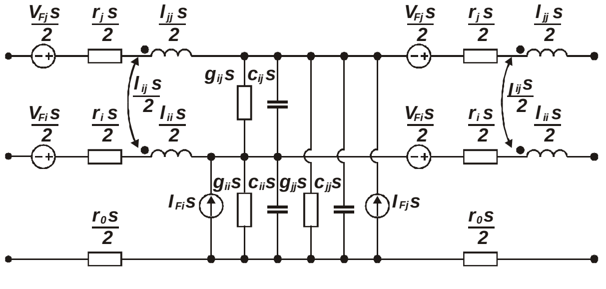

Figure 4: Equivalent T-circuit for a MTL segment with incident field illumination

Other basis circuits like Gamma- or Pi-circuits can be applied too. For the following investigations T-circuit elements were used. The segmentation has to reflect the wavelength, the inhomogenity of the incident fields, the non-uniformity of the line, the termination impedances, and - if necessary - branches. In the result section some rules for segmentation will be given.

2.2 Calculation of the MTL-parameters

In the second step the MTL parameters have to be calculated for each segment, for plain configurations it is quite often sufficient to use analytical approaches [9]. The per unit length capacitance *C'ₛ* and inductance *L'ₛ* of a single transmission line with wire radius of *r* and distance between wires of *d* in free space can be calculated with:

$$C_s' = \frac{2pe_0}{\operatorname{arcosh}(d/r)} \quad \text{and} \tag{1}$$

$$L_s' = \frac{m_0}{2p}\operatorname{arcosh}(d/r)\cdot \tag{2}$$

For a single wire over an infinite ground plane this formulas have slightly to be changed. If the configurations are more complex, numerical method methods like given e.g. in [10] must be applied.

2.3 Field calculation close to metal surfaces

In the 3rd and 4th step the field along the wire-coordinates without wire is calculated with a 3D field solver. The field and current calculations presented here are done with the MoM. Special care has to be taken when the field close to metal planes is calculated [11,12]. To calculate the equivalent voltage and current sources it was shown for fields close to a metal plane, that the highest accuracy can be archived when the E-field perpendicular to the metal plane and the H-fields parallel to the metal plane are taken into account for calculation [12].

2.4 Calculation of the currents and voltages for a line segment

The incident external fields are modeled in the T-circuit (Figure 4) as lumped voltage and current sources. It is assumed that the fields are sufficient homogeneous in the close vicinity of each line segment. For a two wire transmission line oriented in the xz-plane of a coordinate system as drawn in Figure 5 the forcing functions can easily be written for frequency- and time-domain fields. Equations (3) and (4) shows the expressions for the voltage and current in the frequency domain for a single segment.

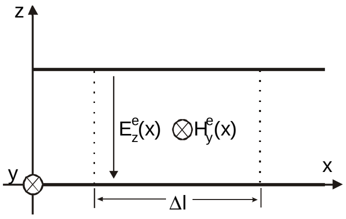

Figure 5: Line segment (2 wires) excited by an incident field

$$U(x,w) = -jw\; m_0 \Delta l \int_0^{h_{eff}} H_y(x)dz \tag{3}$$

$$I(x,w) = jw\; C'\Delta l \int_0^{h_{eff}} E_z(x)dz \tag{4}$$

Equations (5) and (6) show the formulas for the voltage and current sources in the time domain.

$$u(x,t) = -m_0 \Delta l \int_0^{h_{eff}} \frac{dH_y(x)}{dt} dz \tag{5}$$

$$i(x,t) = C' \Delta l \int_0^{h_{eff}} \frac{dE_z(x)}{dt} dz \tag{6}$$

For many configurations the integral in equations (3) to (6) can be replaced by a simple multiplication. The average field or field derivative times the distance gives a sufficient accurate value.

The situation becomes more complex when the wires in free space or the wires with reference ground plane are arbitrarily oriented in the field. A 2-wire segment is fully described with 4 points in free space (P_n, P'_n, P_{n+1}, P'_{n+1}) like shown in Figure 6. The wires in the figure are labeled with w_{n+1} and w'_{n+1}. To take a ground plane as reference conductor into account the lower wire segments and the vectors P'_n-P_n and P_{n+1}-P_n have to be perpendicular to each other. With the help of the 4 points two vectors $\vec{n}$ and $\vec{m}$ can be constructed. These vectors give the average orientation of a line segment in free space.

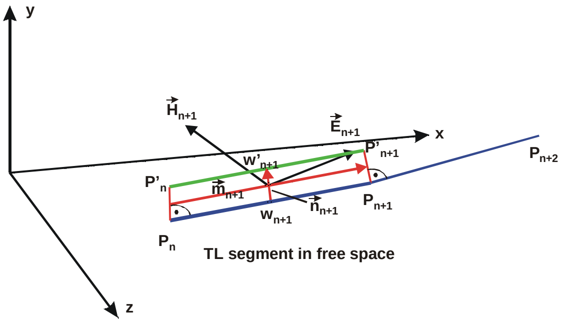

Figure 6: Geometry for a line segment (2 wires w and w') in free space excited by an inhomogeneous incident field

It was already mentioned, that in the case of sufficient homogeneous fields in the close vicinity of a segment it is sufficient to calculate the E and H field at the intersection point of the vectors $\vec{n}$ and $\vec{m}$. The TL-relevant fields for equations (3)-(6) can be calculated with the following vector formulas:

$$H_{TL} = (\vec{m} \times \vec{n}) \cdot \vec{H} \tag{7}$$

$$E_{TL} = \vec{n} \cdot \vec{E} \tag{8}$$

If the homogenity-assumption doesn't apply, formulas (7) and (8) have to be evaluated inside the integral of formulas (3) to (6).

2.5 Generation of a sub-circuit for a field excited transmission line

The generation of the sub-circuits is done with the above given information. A special computer program was written. It splits the line into segments and processes the line and field information to a SPICE subcircuit.

2.6 Calculation of the termination response

The calculations of the termination responses were done with a freely available SPICE 3f5 program (SPICE OPUS) on a PC. The use of SPICE has the great advantage that each electronic circuit that can be computed with SPICE can be integrated as a termination for analysis. All analysis methods like 'AC' or 'Transient', that SPICE offers, can easily be used for computation. The performance is quite good, lossless transmission lines with more than 1000 segments could be calculated with a common PC within less than one minute.

3. Results

Several configurations were investigated and parameter dependencies were studied. Selected results were presented here. The results of the MoM calculations are assumed to be reliable and give a standard to compare to.

3.1 Influence of the number of circuit segments

An important topic is the selection of a sufficient number of segments for the modeling of a wire. The number of elements has to be chosen according to the highest frequency, the ratio of termination impedance to line impedance [13], the shape of the incident field, the line non-uniformity and the branches. In this part the dependency on the termination impedance and the frequency is discussed.

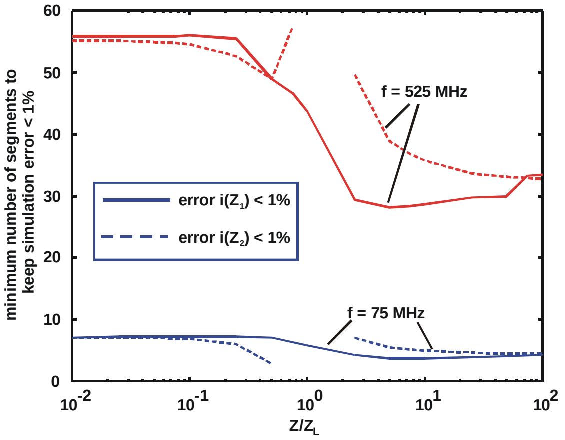

Figure 7: Threshold for the minimum number of segments to keep error of currents on near- and far-end below 1%, depending on termination impedance (relative to line impedance Z_L) and frequency. Uniform TL illuminated by a plane wave, "endfire" excitation (line length 1 m, distance between wires 1 cm, wire radius 0.5 mm, Frequencies 75 and 525 MHz)

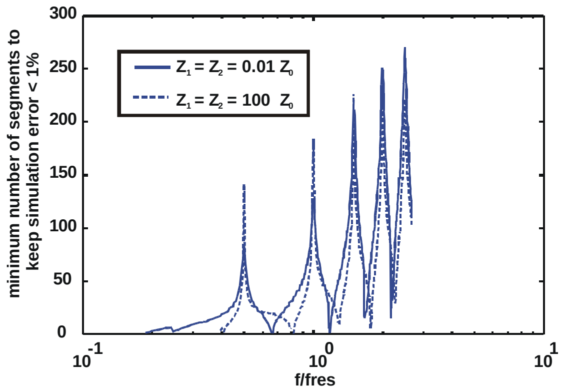

Figure 8: Threshold for the minimum number of segments to keep error of currents on near- and far-end below 1%, depending on the frequency and termination impedance normalized to f_{res} (300 MHz). Wire illuminated by a plane wave, "endfire" excitation (line length 1m, distance between wires 1 cm, wire radius 0.5 mm)

Figure 7 shows the minimum number of line segments for a certain configuration to keep the calculation error below 1% for two frequencies, depending on the termination impedance. The wavelengths belonging to the frequencies are L/4 and L 7/4 (L = line length). The current through Z_2

becomes zero at these frequencies, when Z_2 is equal to the line impedance. The curves are shifted by a factor of approx. 7. This factor represents the frequency difference too. From this plot a rule of thumb for segmentation can be conducted: As long as the termination currents are sufficiently high compared to the minimum (zero points) approx. 30 segments per wavelength are sufficient to keep the calculation error in the range of 1%. The restriction to "sufficient high" currents is for EMC considerations not critical. Mainly the maximum currents are of interest. The results in Figure 7 are in agreement to results in [14] for non-field-excited transmission lines. But here could be shown that depending on the load impedance the relation between maximum frequency and number of segments is not a constant.

Figure 8 shows the minimum number of segments for the same wire but in dependency of the frequency and the termination resistance. In the points when the necessary number of segments increases, the currents in the terminations becomes zero. The above given rule of thumb is still applicable.

3.2 Comparison to MoM and analytical TL-formulas

The LCTL approach was compared to results from MoM computations and results from analytical formulas for uniform TL excited by a homogeneous field. The analytical solution was calculated with the formulas for TL with incident field excitation given in [15]. Figure 9 shows the current on near - and far-end of a uniform TL of 1 m length excited by a plane wave incident field. The results calculated with LCTL are in good agreement with the results of the other methods.

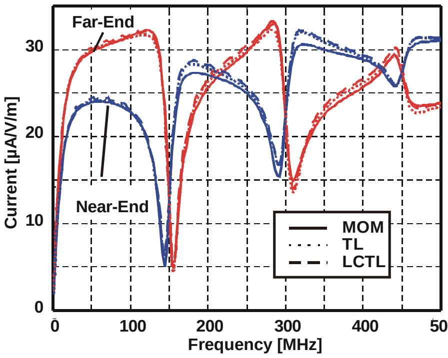

Figure 9: TL in free space. Comparison between MoM calculated currents in terminations and the lumped circuit approach with 100 segments (--), (line length 1m, distance between wires 1cm, wire radius 0.5 mm, terminations on both ends 50 Ohm, broadside, 45° elevation)

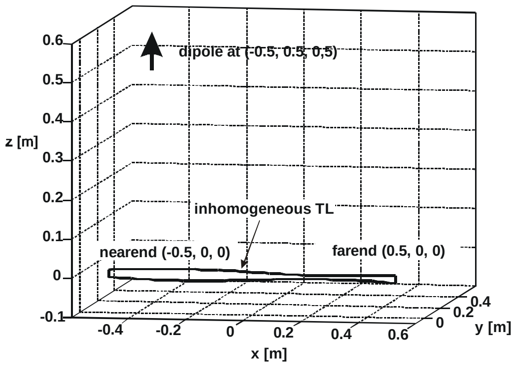

Figure 10: Inhomogeneous TL excited by an electrical dipole (line length 1 m, distance between wires = 0.02+0.01 sin(2 pi (x+0.5)) m, wire radius 0.5 mm, termination impedance on both ends 400 Ohm, excitation by an electrical dipole (I dl=1 Am))

3.3 Coupling of an inhomogeneous field into a inhomogeneous wire above a ground plane

To show the capability of this method to handle non-uniform transmission lines and inhomogeneous field, a non-uniform TL was illuminated by a small electrical dipole (Figure 10). The TL was sinus-shaped with a minimal distance of 1 cm and a maximal distance of 3 cm. Figure 11 shows the currents for near- and far-end of the line in dependency of the frequency calculated with LCTL and MoM. The results are in very good agreement.

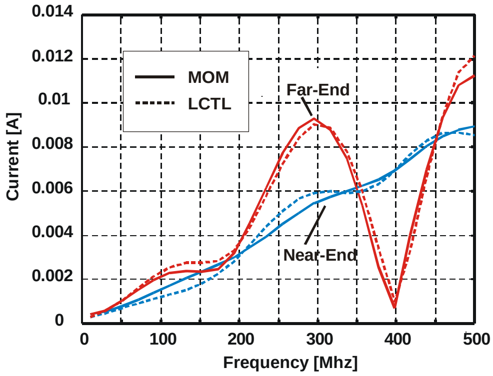

Figure 11: Nonuniform TL in inhomogeneous field (geometry from picture above). Comparison between MoM calculated currents in terminations and the lumped circuit approach with 50 segments (--)

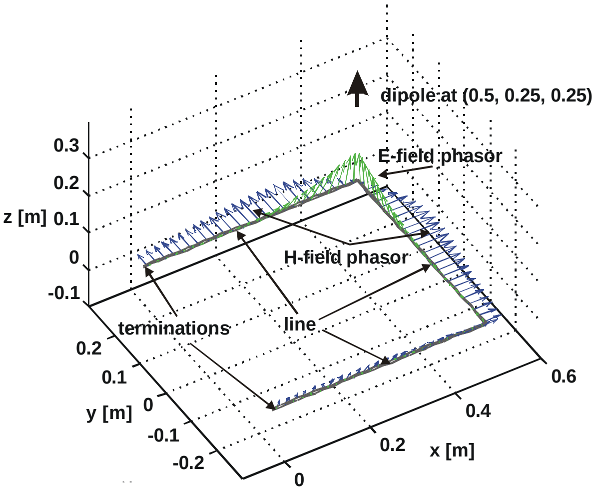

Figure 12: U-shaped wire excited by a dipole located close to an edge with field phasors (wire length 1.5 m, wire radius 0.5 mm, distance between wires 1 cm, 75 line segments, termination impedance 400 Ω)

3.4 Coupling into an U-shaped wire

In cars the TL's are nearly never straight lines. To check the accuracy of the method with bend wires an U-shaped TL, illuminated by a dipole located over one bend was investigated. Figure 12 shows the configuration and the field distribution along the wire. The currents at the terminations were calculated with LCTL and MoM.

Figure 13 shows the results. The currents are shown in dependency of the frequency. For the higher frequencies the matching is quite good, the peaks are a little bit shifted. For lower frequencies the results were not in very good agreement. Nevertheless, the maximum error is around 10%, which is a quite good value for EMC-considerations. The calculation of a U-shaped wire is problematic with TL-methods because of the non-TEM fields at the edges. The reasons why these problems are more obvious in the lower frequency range are not clear yet.

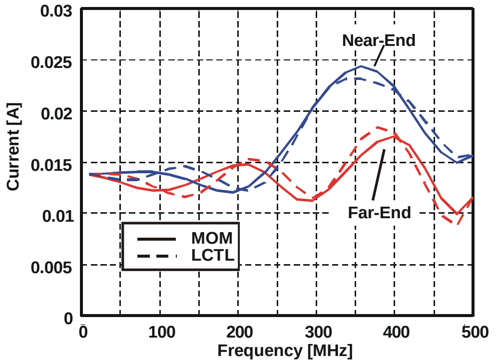

Figure 13: Currents at the terminations of the U-shaped TL. Calculated with LCTL and MoM

3.5 Transient-coupling into a wire over a metal plane

To show the validity of the given method for an incident transient field and a wire over an infinite ground plane we compare here to results gained with LCTL with results given in literature. In [15] a TL over an infinite ground plane (Radius 0.25 mm, height 2 cm, length 1 m) is excited by an electromagnetic ramp-pulse (sidefire excitation) with changing rise times of 1, 10, and 50 ns.

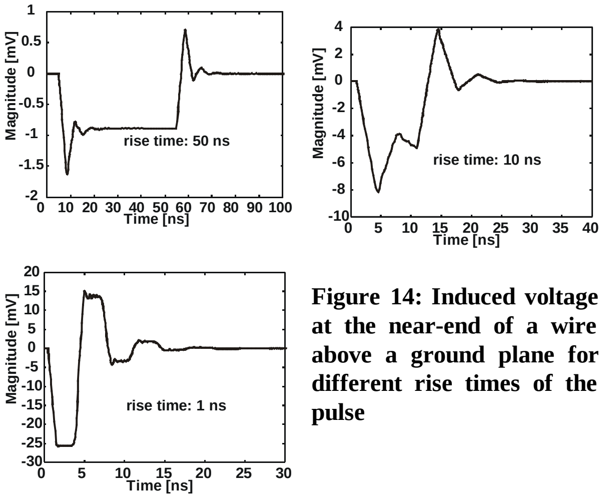

Figure 14: Induced voltage at the near-end of a wire above a ground plane for different rise times of the pulse

The results calculated with LCTL are shown in Figure 14. The line was modeled with 50 segments. The calculated results are in perfect agreement with the literature data.

3.6 Coupling of a transient pulse into a non-uniform transmission line terminated with CMOS-Inverters

As a last result the calculation of the terminal voltages of a transient, inhomogeneous field excited, non-uniform TL terminated with CMOS-inverters is presented.

The TL is illuminated by the fields of an ESD: The field of a transient excited dipole can give a rough approximation for the field of an ESD event [16]. A better approximation is a transient current source with connected wires (total length 1m, center fed) that approach a radiating structure. For the calculation we excited the source with a double exponential current pulse having a rise time of approx. 2 ns and a fall time of approx. 5 ns. The current amplitude is 5 A. The generated fields couple into a non-uniform (sinusoidal-shaped) TL of a 0.2 m length, terminated at both ends with CMOS-inverters. A simple model for a CMOS-Inverter can be found in [17]. The schematic of the investigated configuration is drawn in Figure 15.

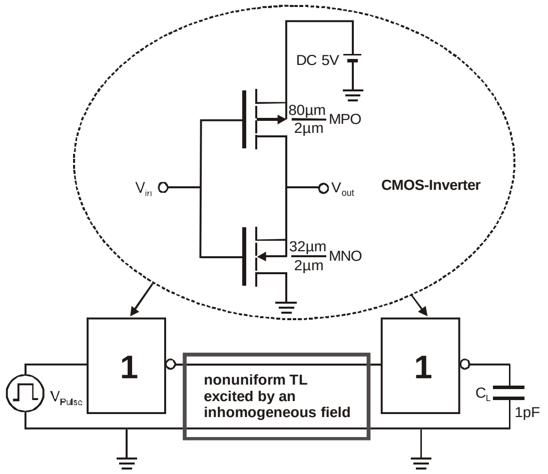

Figure 15: Schematic for an investigation of ESD fields that couple into a nonlinear terminated transmission path

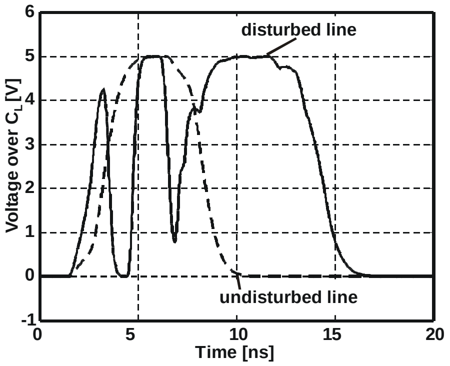

Figure 16: Calculated voltage over the output of the inverter

Figure 16 shows the voltages over the output capacitance of the undisturbed and the disturbed inverter.

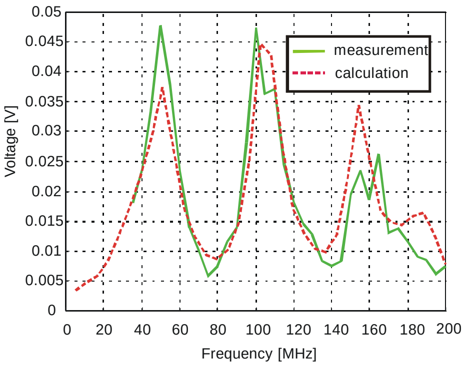

Figure 17: Calculated and measured voltages over the terminations of a single wire located in a stripline

3.7 Comparison of calculations to measurements

A stripline according to ISO 11452-5 standard is a common device in automotive EMC-testing. A 50 Ohm stripline was used to excite an U-shaped single wire that was placed according the ISO standard. The wire was terminated at both ends with 50 Ohms. The total length of the wire was 2.9 m. The input power of the stripline was 0 dBm. The voltages on the terminations were measured and compared to LCTL-calculations with 145 line segments. The fields were calculated with MoM.

The results are shown in Figure 17. The match is quite good but not perfect. The main reason for the deviation is the not perfect MoM-model of the stripline, that was applied, as other calculations and considerations have shown.

4. Discussion

A new method was presented together with some examples. The pros and cons are now discussed here.

One general disadvantage of TL is it, that this method can't predict antenna mode currents. This disadvantage is not a serious objection for our EMC-susceptibility considerations. The line has at the terminations small cross-sectional dimensions. According to Kirchhoffs's law the total current has sum to zero. This means the antenna mode current not predicted by the TL-equations must go to zero and has nearly no influence on the terminal currents [15]. Another objection is, that this method can not handle radiation losses or sections with non TEM-fields. Our investigations shows that the radiation losses for typical practical configurations seems to be low, as the differences between results when compared to MoM are low. The non-TEM-fields as they appear in the edges of the investigated U-shaped TL doesn't result in a high calculation error. These few disadvantages can be compared to a list of advantages of the presented method:

- The 'segmentation problems' of 'pure' MoM could be overcome.
- Inhomogeneous fields close to ground planes can be considered.
- Depending on the segmentation a very wide frequency range can be covered.
- With appropriate segmentations non-uniform transmission lines can be considered.
- Complicated Multiple Transmission Lines can be modeled.
- Nearly arbitrary terminations can be treated. Each termination that can be modeled by the applied circuit simulation program can be calculated.
- Transient as well as CW fields can be taken into account.
- Skin effect can be easily modeled with frequency dependent resistors [9].
- Via transfer impedances [12] coupling into shielded cables can be calculated.
- Differential mode coupling into twisted pair cables can be modeled.

5. Conclusion

A new very powerful hybrid method to calculate the termination voltages of a field excited transmission line is presented. This method combines 3D field solvers, Transmission Line theory and circuit simulation programs. It could be shown that many problem classes could be treated with this approach. With this method the problem of the extremely fine structure segmentation when wires are modeled close to large metallic structures can be overcome. The subdivision of a wire into small segments allows to calculate problems with non-linear elements, inhomogeneous fields and non-uniform TL's. The calculation of the generated equivalent circuit for the cable system with a circuit simulation program allows the application of all terminations (nonlinear, active) and analysis methods (transient, ac) that can be handled with a circuit simulation program.

6. References

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