Calculation of Low Frequency EMC Problems in Large Systems with a Quasi-Static Approach

S. Frei

Audi AG
EMC Department
85049 Ingolstadt, Germany
stephan.frei@audi.de

R. G. Jobava, D.Karkashadze, A.Gheonjian,
E.Yavolovskaya

EMCoS
8 Ingorokva Str. 0108 Tbilisi, Georgia
roman.jobava@emcos.com

Abstract – **Low frequency problems in automobiles and other systems can be calculated with quasi-static approaches. Such approaches can be valid for frequencies up to 10 MHz in automobiles. The method presented here is based on calculation of mutual and self capacitances as well as inductances of all important objects. An equivalent lumped circuit is constructed based on the resulting L- and C-matrices. This paper presents a new solver for the calculation of mutual and self capacitances and inductances of arbitrary three dimensional objects. It is shown how typical low frequency problems can be solved. Accuracy of the method is proved by comparison with direct Method of Moments (MoM) solution and with measurements.**

I. INTRODUCTION

In automotive EMC numerous problems occur in the low frequency range, immunity and radiation problems. E.g. AM radio reception problems are due to the increasing use of power electronics prevalent and need special care. The frequencies of interest in this case are in the range between 0.15 and 2 MHz.

A direct full wave calculation e.g. with the Method of Moments (MoM) in the low frequency range is problematic. The reason is, that for low frequencies the system matrix elements lose information about magnetic potential because of predominance of the scalar potential term. This introduces errors in determination of currents. One of the common ways to avoid lose of accuracy is to generalize a set of basis and test functions. Nevertheless a frequency sweep is necessary and for each frequency a dense complex matrix needs to be inverted. Also the other limitations of MoM apply like modeling of non-linear electronic devices.

If structures are much smaller than the shortest wavelength a quasi-static approach for the calculation might have many advantages. Much smaller means the shortest wavelengths are 8 up to 10 times longer than the longest structures. A chassis having an extension of 4 m can be calculated following this rule up to approximately 10 MHz. The advantage of the quasi-static approach combined with the calculation of an equivalent circuit is, that when the coupling matrices are calculated, the problem is reduced to the calculation of an electrical network.

Equivalent circuit approach considers physics of the phenomena on low frequencies and is faster than direct MoM

calculation. Only one time a real matrix needs to be inverted and the solution is valid for all frequencies the premises apply. After capacitance and inductance matrices are obtained, equivalent circuit approach gives possibility to model different linear and non-linear terminations without significant additional calculation time, while in direct MoM approach each case needs a new calculation for several frequencies. Non-linear terminations can not be handled with direct calculation at all. Also time domain calculations can be easily done with an equivalent circuit. Advantages of equivalent circuit approach thus are doubtless.

However, accuracy of this approach is not well studied for common automotive EMC problems. This paper tries to fill partially this gap and investigate the question for typical low frequency EMC problems arising in automotive industry:

- Crosstalk between cables which have common paths or are located in close proximity to each other. Different complex filter structures for reducing noise can be considered without additional time-consuming calculations

- Coupling of signals from cables to car antennas and vice versa. Here finding position of antennas or cables, which result in reducing of coupling, or construction of special appropriate filters are common tasks

In common EMC problems, where equivalent circuit method can be used, we have number of objects. Some of them are surface objects and others are wire objects. Antennas and cables are connected to each other or to the ground via some circuits. When applying equivalent circuit approach, we must remove all interconnection of objects under investigation and attribute to them some static potential. Value of the potential for the given object has no importance, because only the difference between potentials plays a role. If objects are directly connected to each other without the interconnecting circuits, they can have one and the same potential. Otherwise they have different potentials. When static problem is formulated as described, it should be solved using an appropriate three dimensional static solver.

In a second step the circuit parameters are extracted from the LC coefficient matrices and an equivalent circuit is formed.

The following sections will present a method for the extraction of the LC coefficients and show based on typical problems the applicability of the quasi-static method.

II. PARAMETER EXTRACTION: SOLUTION OF STATIC 3D PROBLEMS

For 3D capacitance/inductance calculations, different methods can be used. The selection of the appropriate method depends on the kind of structure. For typical automobile EMC problems the most powerful and promising method is the Method of Moments, MoM. Basics of the Method of Moments are described in [1].

In the developed program, which is called Static3D and is based on the MoM approach, the following numerical procedures for determining the static charge distribution on arbitrary-shaped 3D surfaces are used. Surfaces are modeled using planar triangular patches. It is assumed that within each triangular sub-domain the charge density is constant [1, 2]. In general, a triangle patch is arbitrarily positioned and oriented in space. The required potential is thus given by

$$V(\vec{r}) = \frac{q}{4\pi\varepsilon_0} \iint_{A'} \frac{1}{|\vec{r} - \vec{r}'|} dA' . \tag{1}$$

where q is a charge and A' is the area of the source triangle. The integration indicated in (1) may be performed either numerically, analytically, or one integral performed analytically and the other performed numerically. However, complete analytical integration eliminates the need for special treatment of the singular integrals, which arise for the diagonal elements of the matrix, and also sidesteps the question of which order numerical quadrature is required to integrate over any given triangular-shaped region. Analytical evaluation of the integrals is also more efficient than numerical integration. To perform analytically the integrations in (1) we follow [2].

Each perfectly conducting surface is charged to a potential

$$\{V_n\}_{n=1}^N ,$$

where N is the number of objects. After that unknown surface charge density distribution on each object is determined by solving the corresponding integral equation using the MoM, the moment matrix is generated by matching potential at the centroid of each triangular surface patch. Solution of the resulting set of simultaneous equations yields values for the surface charge density at the centroids of the sub-domains.

For a collection of N unconnected perfectly conducting objects, we obtain a system of equations for N right hand sides. As a result, charges for each distribution of potentials on objects are found and the following relation between charges and voltages applies:

$$V_n = \sum_{k=1}^N \alpha_{nk} Q_k , \text{ where } n=1,...,N.$$

Matrix of potential coefficients α_{mk} is uniquely determining the matrix of electrostatic induction coefficients:

$$|\beta_{mk}| = \frac{1}{|\alpha_{mk}|}$$

There is a following relation between this matrix and the capacitances matrix:

$$C_{kk} = \sum_{n=1}^N \beta_{nk} , \ C_{nk} = C_{kn} = -\beta_{nk} > 0$$

Coefficients of inductance matrix are calculated as follows:

$$L_{nk} = \alpha_{nk} , \ \varepsilon_n = 1 \ (n = 1,...,N)$$

in suggestion that we have only permittivity of vacuum.

Such an approach was tested with a number of benchmark problems and showed both high speed and high accuracy.

III. HYBRIDIZATION OF MoM WITH MAS

It is known that when wires and surfaces are located close each to other, MoM calculations based on classical uniform charge distribution have difficulties to reproduce accurately mutual capacitances and inductances. Reason is obvious: on close distances objects are strongly influencing each other and charges are distributed very non-uniformly. As a result there is a change of charge within each element. In this case either MoM elements should be chosen small, or new approaches must be used. When we consider surfaces, it is easy to imagine sub-triangulation of surface till the level, when each triangle bears homogeneously distributed charge. However, when wires are considered, decrease of the length of wire is not helping, if any other object is located extremely close to the surface of wire. Charge in this case is distributed non-uniformly along the perimeter. Surface of wire segment must be divided onto strips and charges at each strip must be found independently.

Question is in which cases such a discretization is necessary and how it can be realized.

Main points, which are to be considered, are twofold. From one side, "thick wire" approach, which includes additional segmentation along the perimeter, can bring enormous increase of number of unknowns. From other hand, there are practical applications, when cables, for example, are bundled tight, so it is not possible to ignore their mutual close proximity. From this consideration it becomes obvious, that strict rules are needed to make decision, whether CPU/memory consuming algorithms must be employed.

We investigated this question for different benchmark problems. One of them, interaction between two parallel wires of limited length, is presented in this paper.

A system of two parallel finite wires is considered (Fig. 1). Numerical experiments show that obtained results can be generalized for more complex system of wires, which are located close to each other. On the basis of analysis of results for benchmark problems we could extract information about critical distance between objects, which is forcing to consideration of non-uniformity of charges along wire perimeter.

It is obvious that in the given problem distribution of charge along the wire perimeter depends on the parameter d/r_{min} (relative distance), where d is distance between centers of wires; r_{min} is the radius of wire with the smallest area of cross-section.
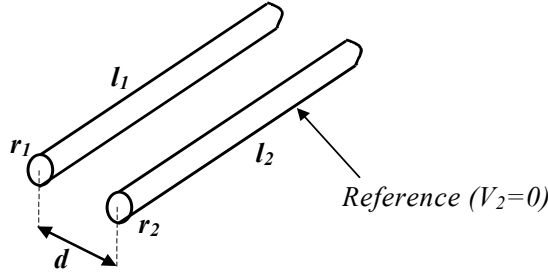
Figure 1.   Two parallel wires on a close distance

In the Table I all geometrical characteristics, which were used during calculations, are listed.

TABLE I.   TWO WIRES ($\Delta\ell$ - WIRE SEGMENT LENGTH)

Entity	Value
ℓ_1 (m)	1.0
ℓ_2 (m)	1.0
r_1 (m)	0.0003
r_2 (m)	0.0003
d/r_{min}	2.03÷12
$\Delta\ell$ (m)	0.0025

When cables are located close to each other, "thick wire" approach is necessary.

In order to investigate dependence of non-uniformity of charge on parameter d/r_{min} we use the following strategy:

- Representation of non-uniform charges is done based on Method of Auxiliary Sources (MAS) [3]. This guarantees minimal additional resources needed for thick wire approach. Number of auxiliary sources and their location is chosen in the way, which gives possibility to achieve high accuracy for the broad range of changes of parameters (Fig. 2)

- To get reference solution for mutual inductance and capacitance, code the Static2D [3] is used. This code provides accurate solution for per unit length values of infinite wires. Parameters of the problem under

investigation, as it can be seen from the Table I, are chosen in the way, that results for 3D case can be compared with 2D results ($\ell \gg d, \ell \gg r$)

- Calculations for LC Coefficients are done (both in 2D and 3D cases) for thick and thin wire approximations
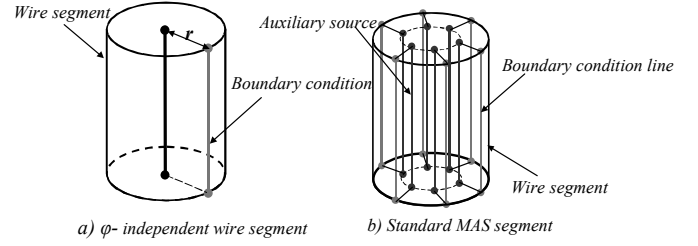

Figure 2.   Auxiliary sources

For situations, when charge is inhomogeneous along the perimeter of wire, for each such segment, having radius r, we generate asymmetric auxiliary source segment of smaller radius r_{aux}.

On the surface of auxiliary segment we place M^{aux} auxiliary linear sources. Each auxiliary source consists of a uniformly charged line of the same length as main segment.

For each auxiliary source we generate appropriate line on the surface of real wire. Number of such lines is equal to the number of auxiliary sources. Along these lines we fulfill boundary conditions. Potential of the m-th wire segment thus is represented with

$$\varphi_m(x,y) = \sum_{n=1}^{M_m^{aux}} q_n^m \varphi_n^m(x,y),$$

where q_n^m is charge of the n-th auxiliary source, associated with the m-th wire segment. $\varphi_n^m(x,y)$ is a potential of auxiliary source. Actually it is a potential of uniformly charged line, having length of the given segment, associated with m-th auxiliary source. Relation between r^{aux} and r, as well as a number of auxiliary sources, depend on the L_{min} - minimal distance of the current segment to other objects (only objects, which are not connected to the considered object are taken into account). These parameters are chosen based on numerical experiments and results are used as a database. Table shows important parameters.

TABLE II.   PARAMETERS FOR CHOOSING THE SET OF AUXILIARY SOURCES

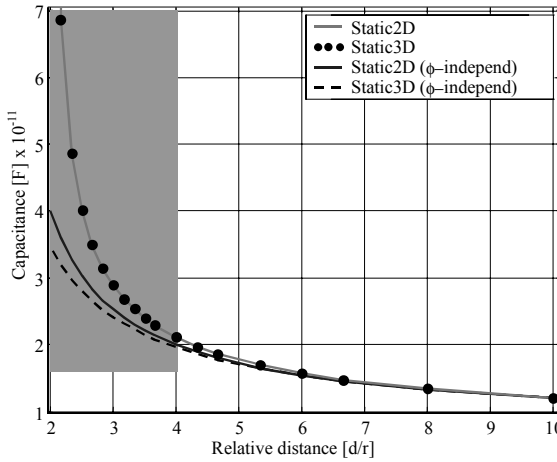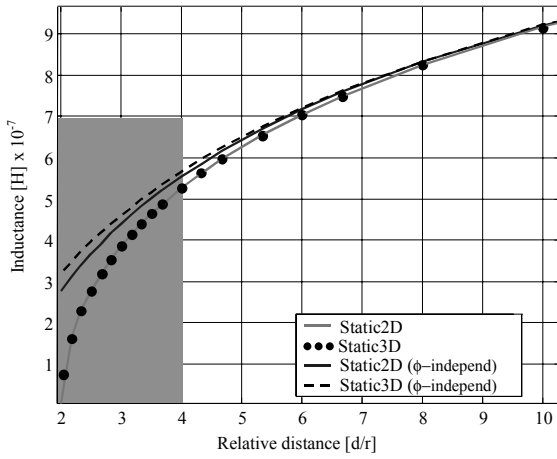| M^{aux}	1	3	5	15
L_{min}/r	8.0	2.0	1.5	1.1
r_{aux}/r	0.1	0.2	0.3	0.6

Results obtained using above strategy are shown in Fig 3.

Figure 3. Dependence of mutual inductance and capacitance of two parallel wires of finite length on relative distance between them
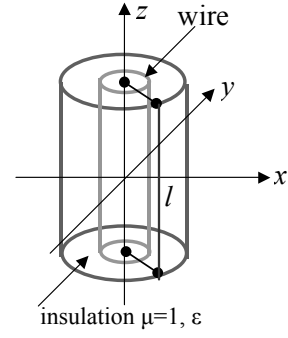

Figure 4. Dielectric covering of wires

In our approach boundary conditions are averaged along generating line l for each wire segment for fixed polar angle φ. Dependence on the angle is considered by the accounting of charge non-uniformity on the core (Fig. 5).
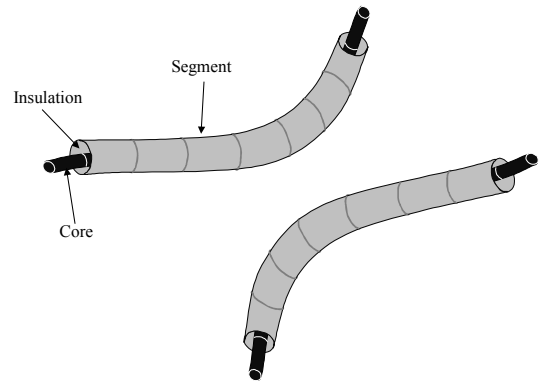

Figure 5. Core segments and insulation segments

Analysis of above results gives possibility to draw the following conclusions:

- MAS modeling as an approach for thick wire problem provides quite high accuracy. For this broad range of parameters (d/r changes from 2.03 up to 12.0) error is not higher then 0.5%

- For distances below $d/r = 4$ uniform distribution of charge gives errors higher than 7% if thin wire approach is used (gray area in the Fig 3)

- For distances higher than $d/r = 5$, there is no need to consider non-uniform distribution of charge, thin-wire approach guarantees here accuracy better than 2%

- Number of necessary (for the given accuracy) auxiliary sources is changing rapidly when distances become very small

Considerations of dielectric coverings for wires have a great importance for LC calculations (Fig.4).

Fig. 6 shows results for wire covered with $\varepsilon = 4.0$ when wire is located above ground plane on the height h. Results are compared with: 1) accurate calculations performed using Static2D; 2) Static2D with $\varepsilon = 1.0$; 3) Analytic formula without consideration of non-uniformity of charge along perimeter of wire (later called as *approximation*)

$$C = \frac{4\pi\varepsilon_0\varepsilon}{\chi}; \ \chi = \ln[(h-(r+d))/(r+d)] - \ln[r/(r+d)].$$

It can be seen that for distance $h/r > 5$ the program Static3D gives quite accurate result (error less than 5%). It is possible to decrease error for lower distances between wire and plane by increasing the number of auxiliary sources compared to those presented in the Table II (in results presented in Fig. 6 we used $M^{aux} = 5$).
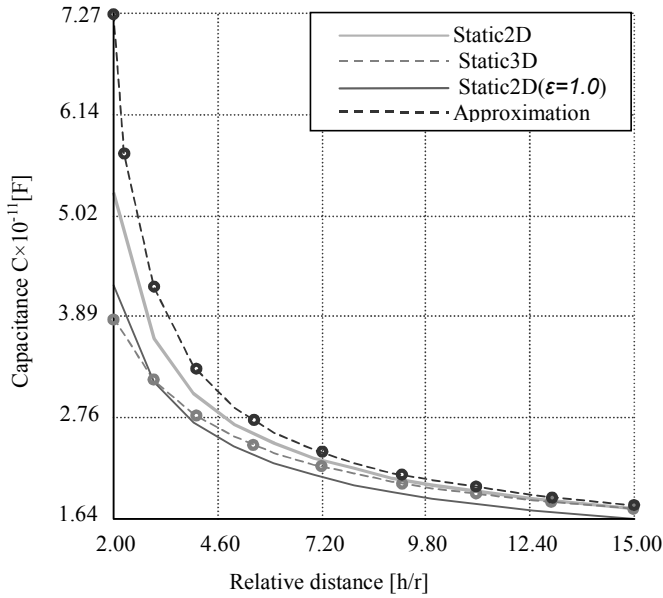
Figure 6. Wire with dielectric covering above the plane. Insulation thickness=$r/3$, $r=0.0003m$, $\varepsilon=4.0$

IV. EQUIVALENT CIRCUIT GENERATION

For the further calculation from the LC matrices an equivalent circuit need to be generated. The following rules can be applied to generate the equivalent circuit for the description of capacitive and inductive coupling between objects

- Wire objects with two terminations are represented with one or several transmission line segments (T- or Pi-scheme)

- Antennas are represented with one or several LC elements

- Non grounded surface objects are represented with capacitance and inductance against zero potential

- EM interaction between objects is modeled as a matrix of mutual capacitances and inductances

- Terminations and direct connections have a direct circuit representation

For example for the case of interaction between antenna and wire in the automobile one can generate the equivalent circuit given in Fig. 7.
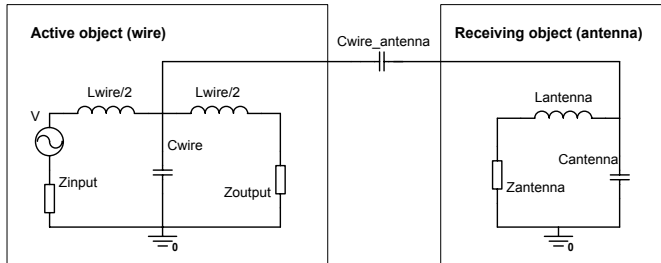

Figure 7. Equivalent circuit

V. RESULTS

Equivalent circuit approach was tested to ensure the correctness of this method.

A problem of crosstalk in the realistic car model with a 2-wire bundle is considered. Distance between wires is d=1 cm. Each wire radius is r=0.3 mm. Height of the wires above the car surface is varying.

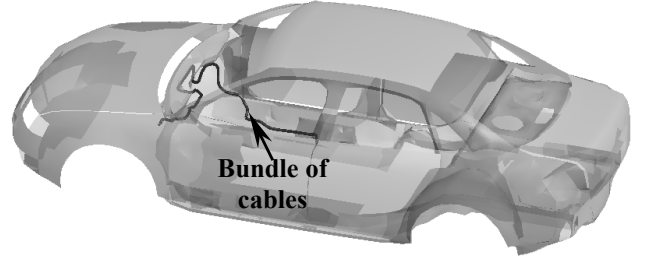Bundle path in the car is shown in the Fig. 8.

Figure 8. Car with a bundle

One of the cables is fed by voltage source with amplitude 1V at the input termination. This wire is called Wire1. Correspondingly the second wire is called Wire2. Crosstalk between these two wires for frequency range from 1 kHz to 10MHz is calculated. Input and output termination loading parameters are listed in Table III.

TABLE III.   INPUT AND OUTPUT TERMINATIONS

Input terminations	Output termination
Wire1-to-GND: coaxial feeding cable	Wire1-to-GND: 5 Ω resistor
Wire2-to-GND: 10 Ω resistor	Wire2-to-GND: 100 Ω resistor

Car body is considered to be the reference conductor.

Following figure represents currents versus frequency for output termination of Wire2. Results of equivalent circuit approach are compared with those obtained by direct MoM solution via electromagnetic solver TriD [4].
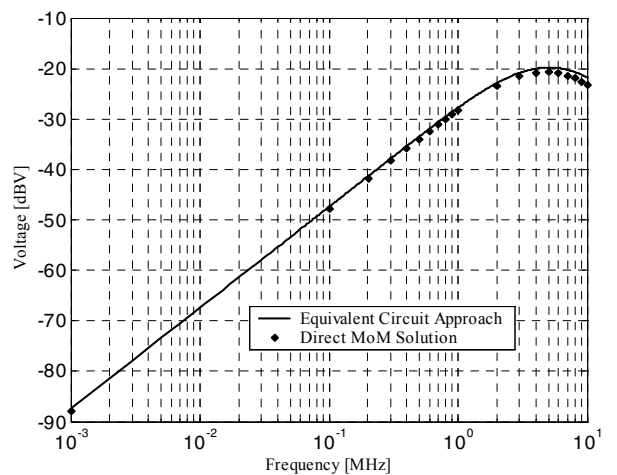

Figure 9. Voltage at output termination of Wire2

It can be seen that equivalent circuit approach gives results, which are very close to direct MoM solution. In order to produce results, corresponding to this graph MoM needs one calculation <u>for one</u> frequency, while equivalent circuit approach needs only one calculation (to determine LC matrices) <u>for all frequencies</u>. Static 3D calculation is also done faster than electrodynamic 3D calculation (for one frequency point) because latter is applied to complex matrix but static calculation applies to a real matrix and is done once to get results for all frequencies.

Consider now coupling from the cable to car antenna. Car model and parts of experimental set-up are shown in Figs. 10-11.
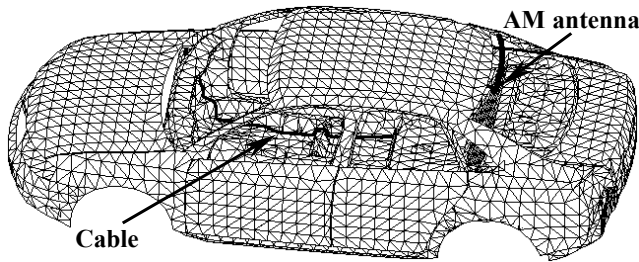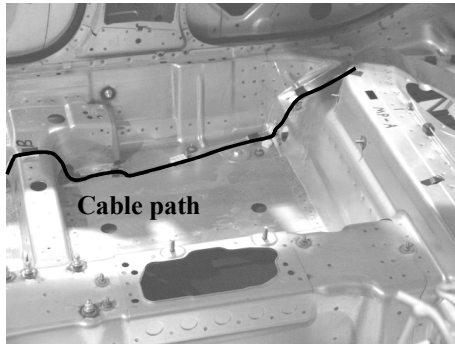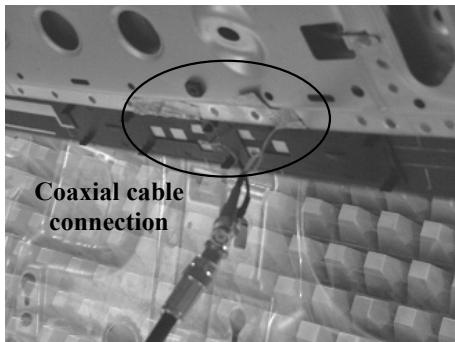

Figure 10. Car model with 15361 surface and 288 wire elements

a) Interior of the car

b) Antenna port

Figure 11. Parts of the experimental set-up

Equivalent circuit for wire, placed in the car interior, and interacting with AM antenna, is shown in the Fig. 7. Comparison of different approaches with measurement is shown in the Fig. 12, where voltage in antenna port is presented versus frequency. Results calculated by equivalent circuit approach are in a good agreement with direct MoM (program TriD) calculation and with measurement.
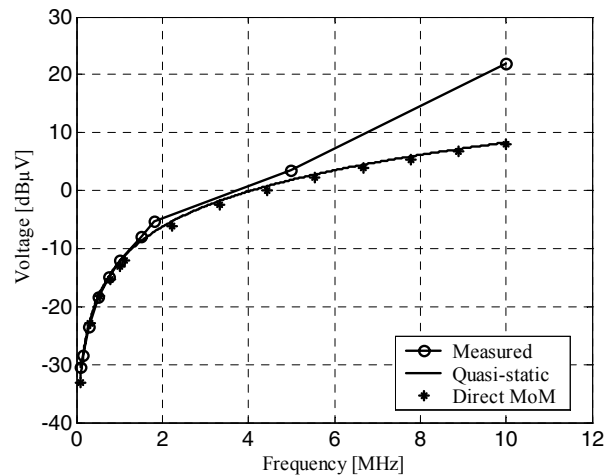

Figure 12. Voltage vs. Frequency

Difference between calculations and measurements above 5 MHz can be explained with antenna amplifier model, which was not adjusted to frequencies above 5 MHz.

VI. CONCLUSIONS

This paper proposes an efficient multi-step quasi-static approach for the solution of low frequency EMC problems. In the first step, the 3D static problem is solved, and capacitance and inductance coefficient matrices are extracted. In the second step an equivalent circuit is generated. In the last step frequency or time domain analysis in the low frequency range is applied to the circuit to determine coupled voltages and currents. The proposed approach is much faster compared with direct MoM calculations and is more flexible for modeling of complex non-linear termination devices in frequency and time domain.

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