Application of Adaptive Scheme for the Method of Moments in Automotive EMC Problems

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Abstract — **Two adaptive schemes for the Method of Moments are presented. Aim of these schemes is performance of automatic re-meshing of geometry based on defined error estimation criteria. First scheme is based on estimation of boundary condition performance. Second scheme is based on consideration of high current and charge values on surfaces. Developed schemes can be efficiently used in solution of automotive EMC problems.**

I. Introduction

For fast and cost efficient development of prototypes in automotive industry with the assured EMC-quality from the beginning, development of efficient simulation tools is needed. The method of moments (MoM) continues to be the most frequently used electromagnetic simulation technique for application to computer-aided engineering (CAE) of the EMC of automobiles. However, method is typically computationally intensive, and therefore is of limited use in the CAE of EMC problems. It is desirable to investigate means of improving the efficiency of full-wave methods in general and particularly MoM, so that typical EMC problems can be simulated in reasonable time.

Several software houses offer commercial MoM-based simulation tools for the EMC problems [1]-[8]. These software packages have the capability to incorporate optimization features either internally [5] or by coupling the MoM simulation engine to external parameterized optimizer [4]. Several researchers are also investigating methods to improve the efficiency of MoM-based simulators so that robust CAE tools and optimizers can be developed for smaller computational platforms. These investigations include the application of wavelet transforms to reduce the size of the moment matrix [9], utilization of symmetries and redundancies in the problem space to efficiently fill the matrix [10], space mapping optimization techniques [11], and order-recursive linear system solvers [12]. Fast solving methods like [13]-[14] are promising, however, today they are limited to high frequency applications.

While using MoM approach, calculation times depend greatly on the level of representation of geometry, i.e. on its discretization. The analysis of a MoM solution shows that uniformly fine segmentation should not be applied to all parts of a structure, as the behavior of currents or/and charges, as well as errors in performance of boundary conditions can be often quite smooth for some parts of the geometry. This suggests the direction of development of an adaptive iterative scheme for MoM. On each step of iteration, the structure must be automatically discretized non-uniformly unless the best solution with a minimum number of elements is found.

When an EMC-engineer designs a surface discretization, the process usually involves a mixture of experience, intuition, and guesswork. If the results of the MoM approximation appear reasonable, then the chosen discretization is accepted; if not, then the discretization is redesigned. The drawbacks of this procedure are obvious. Without an a-posteriori error estimate there is no reliable way to judge the acceptability of the numerical solution. If the engineer's intuition fails when designing the discretization, it is also liable to fail when evaluating the worthiness of the results. Furthermore, if the initial solution is rejected, then the analyst must prepare an entirely new set of data, representing the new mesh. This is very costly and wasteful procedure without any guarantee that the new discretization is sufficiently accurate.

Consequently, adaptive approach and a-posteriori estimates of an accuracy of numerical solutions are of great interest. However, despite some recent publications on the adaptive mesh refinement in the application of MoM methods, the basic notions, aims and goals, principles for comparisons etc. are not yet well established.

This paper aims to fill up this gap.

II. Method

A. Conventional MoM approach

MoM geometry modeling stages in automotive EMC are the following:

- The FEM mesh for mechanic analysis (i.e. crash simulation) is given as initial geometry data (see Fig. 1). This mesh usually contains from 200,000 up to 500,000 elements. Besides of the unacceptably big size of matrix, which would be generated if such mesh was directly used with MoM approach, it contains number of small geometry objects (details), which can be omitted from EMC modeling point of view. Therefore, initial mesh needs re-meshing or coarsening

- After re-meshing, the basic computational model is prepared. Usually it contains approximately 10,000 elements (Fig. 2)

- Using this basic model, special models for considered problems are prepared. They contain more elements (about 15,000), because areas of interest have higher discretization

Therefore, MoM approach can be characterized with the following steps:

- Re-mesh surfaces and wires uniformly if possible, or choose based on intuition regions which must be re-meshed non-uniformly
- Perform initial calculation
- Check for convergence
- Repeat the steps until convergence is reached

Questions, which arise, are:

- How to find critical regions on mesh automatically?
- Are there further criteria but the convergence indicating the quality of the result?

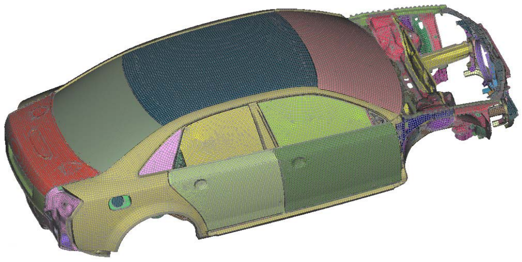

Fig. 1. FEM mesh for mechanic analysis (319,519 elements)

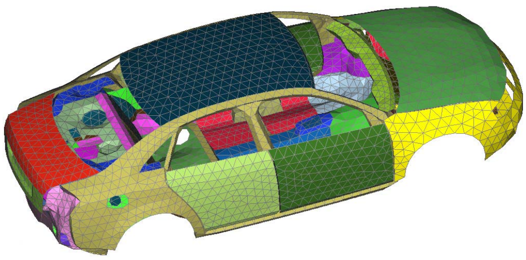

Fig. 2. Basic mesh for EMC calculation (10,000 elements)

In order to answer these questions, we have performed investigation to find dependence of results on the level of discretization. Our experience was accumulated in the set of criteria, which can govern automatically non-uniform adaptive discretization of the surface. These criteria can be applied to the analysis of boundary conditions performance. Another option considered is analysis of the current and charge densities on the geometry elements. In this section we describe ideas, which assist to generate set of criteria and also details of both approaches together with their relative advantages and disadvantages.

B. LSDM (Level-Surface-Difference-Minimum) Adaptive Scheme

Numerical approaches for adaptive grid refinement are working in a hierarchical way. First, one starts with a 'coarse' mesh, which gets recursively refined. Depending on the error indicator or error estimator, certain global refinement steps should be performed, or mesh refinement should be performed only locally. The final mesh will be highly adapted towards minimization of the error of boundary conditions performance, or towards sufficiently good description of areas, which accumulate high values of charges or represent high currents, depending on the scheme, which is used. Far away from the critical areas, grid size will be significantly larger.

Main ideas of the developed adaptive scheme arise during examination of manual non-uniform re-meshing. After performance of initial calculation (iteration 0), values of interest (current and charge densities, errors in boundary condition performance, etc.) must be analyzed. It is supposed that all triangles, where value of interest (for example partial error) is higher than some prescribed value L (Level-criterion), must be re-meshed. However, it can appear, that area of triangles, chosen for re-meshing according L-criterion, is too big or too less compared to the total surface area of the object. There is also an option that during several iterations area of chosen triangles does not change since algorithm is choosing the same part of the surface for successive re-meshing. In order to reflect these options, we form three additional criteria: S-criterion (or surface criterion), D-criterion (difference criterion) and M-criterion (minimum criterion).

Meaning of these criteria is the following. If surface area chosen for re-meshing is higher, than certain value S given in percentage from the total surface area, it is supposed that re-meshing of such a big area is too expensive from computational point of view. In this case, L-criterion is automatically increased, until S-criterion is reached. Thus, algorithm allows re-meshing of only S percent from the total surface area of the object. Also, meeting of S-criterion does not guarantee that re-meshing will be performed and further iterations will be done. Last two criteria, so called D- and M-criteria, must also be met.

It is possible, that area of triangles to be re-meshed does not differ from that, chosen for previous iteration. D-criterion, or difference criterion shows in percentage level of difference between surfaces chosen on the current and previous iterations. If difference is smaller than a prescribed value D, iterations must stop. This seems to be reasonable if one makes assumption, that sequential re-meshing of the same part of the surface is not seriously improving accuracy.

If area chosen for re-meshing is too small compared to the total area of the surface of the object, at least smaller than certain prescribed value M (M-criterion), iterations must stop since re-meshing of very small parts of the surface is not likely to improve solution in general.

If chosen four criteria (L-, S-, D- and M-criteria) did not stop iterations, re-meshing of the surface and further calculations must be performed.

Algorithmically LSDM scheme can be described with the following steps:

Initial calculation:

- Perform calculations with initial mesh. Analyze values of interest, on which adaptive approach is based

Check L-criterion:

- All triangles having observation value between L% and 100% from the maximum will be considered as triangles for re-meshing

Check S-criterion:

- If area of the set of triangles chosen for re-meshing is higher than certain value S, given in percentage from the total surface area, increase automatically L-criterion, until S-criterion is reached

Check D-criterion:

- Check if difference between surfaces chosen on current and previous iterations differs more than prescribed value D% (D-criterion). If difference is smaller than D, iterations must stop

Check M-criterion:

- Check if area of chosen surface is more than prescribed value M%, measured in percentage from the total surface area (M-criterion). If difference is smaller than M, iterations must stop

Further iterations:

- If previous criteria did not stopped iterations, re-meshing of the surface and further calculations must be performed

During the such approach, several calculations may be required. Additional time will be spent for error calculations, but the total time in most cases will be lower than that needed for the convergence studies based on homogeneous discretization.

C. BCP (Boundary Condition Performance) Based LSDM approach

Recent investigations [15]- [17] have shown, that it is possible to control accuracy of MoM calculations based on estimation of boundary conditions performance (BCP). Analysis shows that a pair of BCP errors [15]- [17]

$$\varepsilon_E[\%] = 100\frac{\int_{Surface} |\vec{n}\times(\vec{E}^{sc}+\vec{E}^{inc})|\, dS}{\int_{Surface} |\vec{n}\times\vec{E}^{inc}|\, dS} \quad (1)$$

$$\varepsilon_H[\%] \equiv 100\frac{\int_{Surface} |\vec{n}\cdot(\vec{H}^{sc}+\vec{H}^{inc})|\, dS}{\int_{Surface} |\vec{n}\times\vec{H}^{inc}|\, dS} \quad (2)$$

calculated for both E- and H-fields is sufficiently enough to totally characterize accuracy of the obtained MoM solution.

The error metrics (1)-(2) are applicable for arbitrary surfaces, including open ones, provide finite values of surface integrals, and perform the proper normalization of error expressions. An error metric (1) directly indicates, how well the obtained solution satisfies formulated problem. However, as found in [16-17], metric (1) is not sufficient enough to totally characterize the near-field errors, and additional error metric (2) for the magnetic field should be also introduced.

The partial BCP errors based on (1) and (2) may be considered to find the contribution of each geometry element to the total BCP error on the structure. Since integrals in (1)-(2) are finite regardless of the surface type, BCP errors are applicable to any surfaces including open ones. And finally, calculation of (1) and (2) does not require knowledge of any other solutions to the given problem, excepting obtained one (so convergence studies are not necessary to judge about accuracy). Therefore, BCP error metric is the most convenient metric to estimate accuracy of MoM solutions on arbitrary configurations.

BCP error analysis gives a possibility to formulate adaptive approach using LSDM scheme. Task flow in BCP based LSDM adaptive scheme is shown in the Fig. 3.

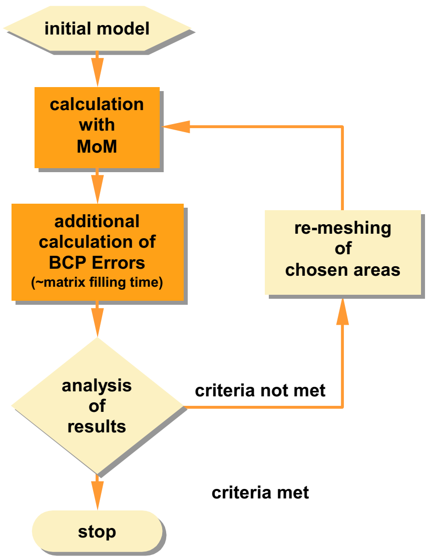

Fig. 3. Task flow of BCP based LSDM adaptive scheme

D. SJQ (Surface Current and Charge) based LSDM Adaptive Scheme

Idea of this approach is based on discretization of areas bearing high values of relative current and charge densities. It is supposed, that if areas, where currents and charges are high, are sufficiently well discretized, it is more likely, that total solution will be accurate.

Fig. 4 shows task flow in SJQ based LSDM adaptive scheme.

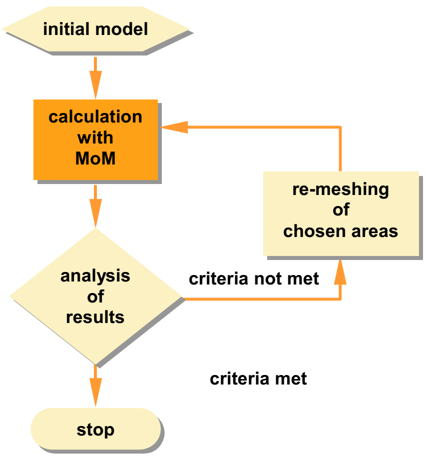

Fig. 4. Task flow of SJQ based LSDM adaptive scheme

E. Difference between methods

In this sub-section we demonstrate difference between described methods in the problem of excitation of sphere by dipole. Radius of sphere is 0.5 m and center is located in the origin of axis. Vertical electric dipole is placed in 10 cm above the surface of sphere, producing highly inhomogeneous incident near field. Frequency of excitation is 300 MHz. Initial geometry is formed by 500 triangles.

Figures 5 – 7 show models for some chosen iterations for different approaches. We compared adaptive approaches to the successive triangulation method, when each triangle was divided onto number of triangles by the same manner as this was done for the chosen triangles in adaptive approaches. Successive triangulation would be an option if so called ‘blind’ approach to investigation of convergence would be used.

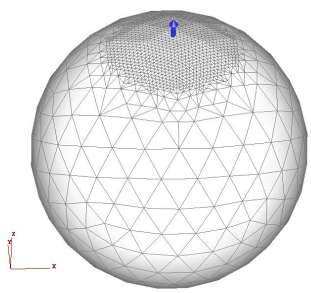

Fig. 5. SJQ approach, iteration 3, number of triangles 2466

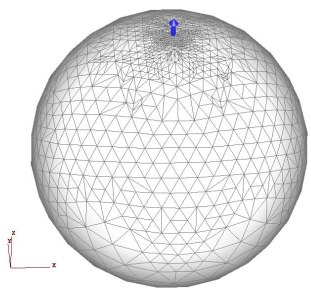

Fig. 6. BCP approach, iteration 5, number of triangles 2388

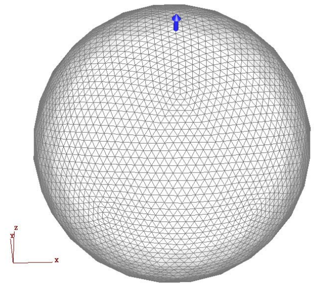

Fig. 7. Successive discretization, iteration 2, number of triangles 8000

Fig. 8 shows BCP error for different approaches depending on the cumulative time of calculation. Computations were performed on Xeon Dual 2800 MHz PC on Windows platform.

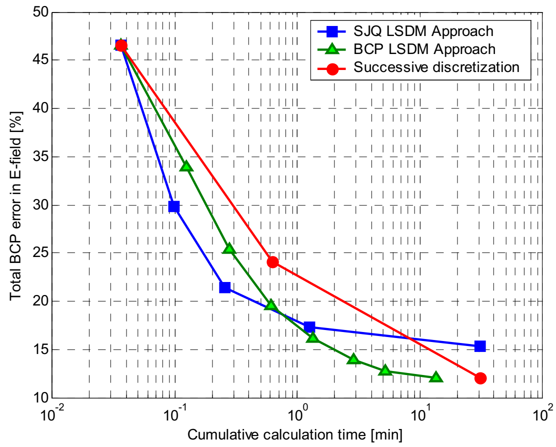

Fig. 8. Dependence of BCP error on computation time

It can be seen that SJQ approach is improving accuracy extremely fast with the first iterations. However, after 4 iterations, SJQ approach reaches criteria of exit from iteration process. By this time, surface discretization is extremely good in areas having high currents and charges, but other parts of the surface are not well discretized. BCP approach is convergent slower than SJQ, but can reach low overall BCP error. If the method is forced to continue iterations by choosing the appropriate criteria, after a number of iterations, total surface will be re-meshed approximately in the same manner as this would be done by successive discretizations (with slightly higher level of discretization in areas of high gradients of the incident fields).

TABLE I shows E_z scattered field magnitude in the point close to the surface obtained by different approaches. Coordinates of the point are: (0.1,0.0,0.51) [m].

Number of unknowns	Successive	BCP_LSDM	SJQ_LSDM
500	$2.9412\cdot10^3$	$2.9412\cdot10^3$	$2.9412\cdot10^3$
1000	N/A	$1.3324\cdot10^3$	$1.3287\cdot10^3$
3000	$1.3298\cdot10^3$	$1.3457\cdot10^3$	$1.3311\cdot10^3$
8000	$1.3371\cdot10^3$	$1.3442\cdot10^3$	$1.3318\cdot10^3$

TABLE I
SCATTERED ELECTRIC FIELD EZ [V/M]

It can be seen, that there is a fast convergence in fields when LSDM adaptive schemes are used. Point of observation is located in the area of highly inhomogeneous currents and charges. Both adaptive algorithms are performing a local re-meshing of this area and therefore are giving a fast convergence of the scattered fields in chosen particular point. However, behavior of BCP approach guaranties improvement of performance of boundary conditions over total surface, while SJQ approach is pointed to improve situation only in the areas where high currents and charges are observed. Latter situation frequently can be observed for the problems where radiating structures, antennas for example, are presented.

Performed investigations give the following conclusions about difference between methods:

- Both, SJQ and BCP based LSDM schemes give improvement of results in the areas, where currents and charges are high
- SJQ based LSDM scheme is effective for very inhomogeneous excitations (transmitting structures, antennas, local sources)
- SJQ based LSDM scheme might not detect problematic receiving structures, while BCP based approach does
- SJQ based LSDM scheme is converging faster than BCP based LSDM scheme and does not require calculation of surface errors
- BCP based LSDM scheme will provide improvement of accuracy over total surface of the object

It should be noted, that in both approaches it is very important to have a good automatic surface meshing tool, which will refine or probably coarsen set of chosen elements together with their neighbor elements, so smooth transition between re-meshed area and remaining part of surface will be guarantied. We have developed such meshing module.

In next section, we consider the application of SJQ and BCP LSDM schemes to the automotive EMC problem.

III. Automotive EMC application

We discuss here problem of investigation of radiation characteristics of bumper rod antenna (see Fig. 9) for the realistic car model. Basic model contains 7376 triangles and 69 wire segments. Model is placed above perfectly conducting ground. Antenna is fed with the voltage source of 1V at the segment, attached to the surface. This segment is also loaded with 50Ohm resistance (in series with the source) to reflect impedance of the feeding coaxial cable. Operation frequency is 433 MHz. For convergence studies we observe value of current in source segment.

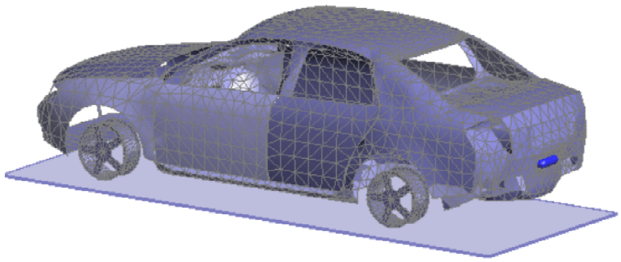

Fig. 9. Car model with antenna in bumper

Consider now application of BCP adaptive approach. We settle error level to 20% (L-criterion). Surface area, permitted for re-meshing is chosen to be not more than 20% (S-criterion). This means, that all triangles, having either σ_E or σ_H (relative partial errors in E- and H-fields) higher than L=20%, are considered as potential candidates for re-meshing. However, if sum area of chosen triangles exceeds S=20% of total surface area, re-meshing will cause serious increase of calculation time. In our case, area of chosen triangles in iteration 0 is 0.234% of total area. D-criterion was chosen as 1% and M-criterion was settled to 0.01%. After re-meshing of these chosen triangles, we get new geometry model, which consists of 7446 triangles.

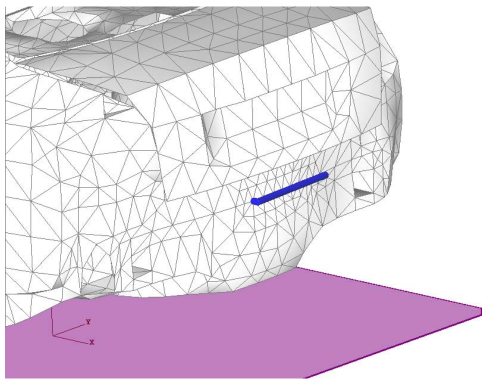

Fig. 10. Model for iteration 1

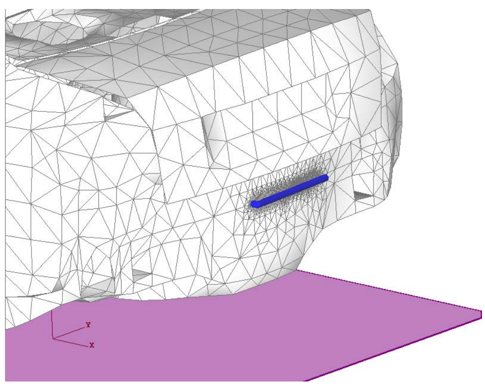

Fig. 11. Model for iteration 4

Next iterations are showing fast convergence of the current in antenna port. Fig. 10 and Fig. 11 show meshes obtained on 1^{st} and 4^{th} iterations in BCP LSDM adaptive scheme.

Behavior of solution for SJQ approach is approximately the same. Results for current in the antenna port are shown in the TABLE II.

Iteration	BCP LSDM		SJQ LSDM	
	Number of triangles	Current mA	Number of triangles	Current mA
0	7376	0.0240	7376	0.0240
1	7446	0.1700	7482	0.1600
2	7606	0.2321	7638	0.2322
3	7870	0.2334	7979	0.2326
Reference solution	Triangles: 29974		Current: 0.2319 mA	

TABLE II
CURRENTS IN ANTENNA PORT

Next figure shows convergence of results obtained with two adaptive schemes discussed in this paper.

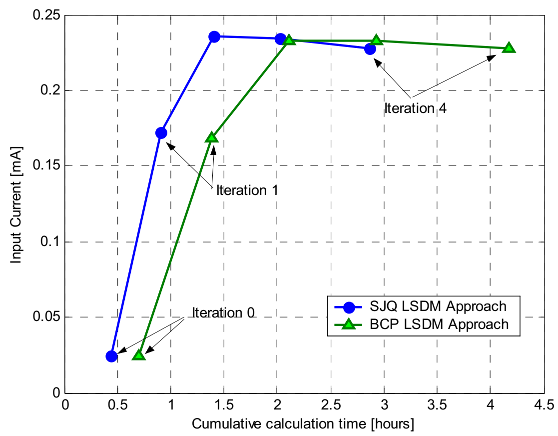

Fig. 12. Convergence

The results presented in this sub-section support conclusions, which were drawn from the comparison of methods for the simple geometry in previous sub-section.

IV. CONCLUSIONS

In this paper two schemes for adaptive automatic mesh refinement within the frame of Method of Moments are presented.

First adaptive scheme is based on estimation of boundary condition performance (BCP). Adaptive scheme exploits possibility to find all surface elements, on which boundary conditions (for both E- and H-fields) are not well satisfied. These areas are refined with automatic re-meshing tool. Iterations continue until prescribed criteria (LSDM criteria) are reached on all surface elements.

Second scheme (SJQ) is analyzing triangles having high densities of currents and charges. Chosen triangles are re-meshed. Scheme is effective for active devices.

It is found that:

- Automatic mesh optimization can be controlled by LSDM scheme regardless of the physical entities used as a basis for observation
- SJQ approach gives a very fast convergence in the problems where currents and charges have high gradients (i.e. antennas, other transmitting structures)
- BCP approach considers both, radiating and transmitting structures, but requires additional calculations
- Adaptive schemes can give, with minimum calculation time, sufficiently high accuracy

Applications from automotive EMC problems are targeted.

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