Coupling of the EM Solver with Mechanical and Thermal Shell Elements

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Abstract

The Electromagnetics (EM) solver of LS-DYNA® has recently been extended to shell elements, in order to solve coupled EM/mechanical/thermal problems on thin plates, which appear in Magnetic Metal Forming and Welding experiments. Due to the magnetic diffusion of the EM fields through the thickness of the plate, which is a very important phenomenon that needs to be precisely solved, the EM part of the simulation still needs a solid mesh with several through thickness elements. This solid mesh, underlying the shell mesh is thus automatically built during the simulation and is used to solve the EM equations. The EM fields are then averaged or summed through the thickness in order to compute equivalent EM fields on the shells, and in particular an equivalent Lorentz force and Joule Heating which are used by the mechanical and thermal solvers. The model is presented and illustrated on some academic and industrial examples. Comparisons between solid and shells are presented.
In a last part of this paper, a different new feature of the EM solver, the computation of magnetic field lines in and around the conductors is presented.

Purpose of conducting shells versus conducting solids

The Electromagnetism (EM) module was introduced a few years ago in LS-DYNA [1]. Some important applications of the module and its coupling with the Mechanical and Thermal solvers of LS-DYNA concern the Magnetic Metal Forming (MMF) and Welding (MMW) of thin conductor plates. Up to now, the only way to do such simulations was to use solid elements to model the thin plates since the EM solver only could handle these elements. One of the reasons for such a limitation was that in general MMF and MMW processes, the current rise time and electrical conductivity of the workpiece are such that the diffusion of the EM fields through the thickness of the workpiece happens at the same time as its mechanical deformation and thermal heating. Solving correctly this diffusion process is capital to get correct EM forces and Joule Heating. For example, if this diffusion is too fast (which happens when the conductor has a low electrical conductivity or the current rise time is too slow), the workpiece will act like a "strainer" and let most of the magnetic pressure go through it without moving much.

In order to correctly solve this EM diffusion through the thickness of the workpiece, we still need to use, on the EM side, solid elements with at least a few elements through the thickness. On another hand, shell elements often have better mechanical and thermal behavior when modeling thin plates. We thus decided to build a solid mesh which is used to solve the EM equations, underlying the shell mesh used for the thermal and mechanical equations.

We will first present in more details the model just introduced, and then show some examples with some comparisons between using only solid elements for the mechanics, thermal and EM (old method); and using shells for the mechanics and thermal and solid elements for the EM (new method).

Presentation of the Model

For each part, we can specify the number of solid element *nsol* in the shell thickness in the *EM_MAT_004 card.

The solid mesh is then built the following way: For each original node shell, N_0, *nsol* new nodes are evenly spread on a segment $[N_0, N_{nsol}]$ which is such that $\overrightarrow{N_0 N_{nsol}} = t_{N0} \times \overrightarrow{n_0}$ where $\overrightarrow{n_0}$ is the unitary normal to the shells at N_0 computed as the average of the normal of the shells connected to node N_0, and t_{N0} is the shell thickness at $\overrightarrow{n_0}$. The nodes are then connected to form a solid mesh, which can be used to solve the EM equations in the traditional EM-LS-DYNA way, i.e. using FEM coupled with BEM (ref [1]). In short, the user inputs shell elements but the EM solver 'sees' solid elements where it solves the classic way. Therefore, no calculation time savings are to be expected on the EM part, the sole purpose of adding conducting shells is to allow users to make use of their properties when coupling with the mechanical and thermal solvers.

Once the EM fields are computed on this solid mesh, the EM force from nodes (N_0, $N_1 \ldots N_{nsol}$,) are added and sent to the mechanical solver as a force acting on the shell node N_0. The Joule heating is averaged over the solid elements in order to give the thermal solver a joule heating for the given shell. The other fields are averaged the same way in order to be output to d3plot as one field per shell.
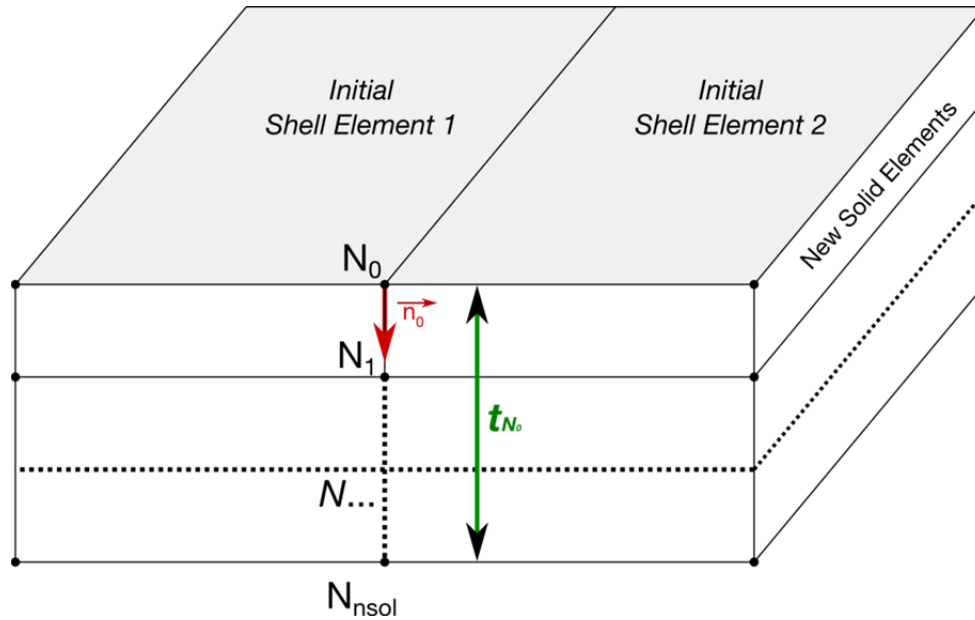
Figure 1 Sketch showing how new solid elements are generated from the initial shell elements

Validation of the model on the TEAM 12 model

In order to validate the implementation of conducting shells, we used an academic EM mechanical problem where the deformations are not too important so that the mechanical differences between shells and solids are minimized. The so-called TEAM 12 problem consists of a clamped beam placed in a uniform magnetic field [2] (See Figure 2). The magnetic field has a first component exponentially decaying with time that generates an induced current in the beam that in turn, interacts with the second constant component of the field and creates a Lorentz force which causes the beam's movement. The TEAM 12 experiments were performed with four different values for this constant field : 0.2, 0.5, 0.7 and 0.9 T. This problem has already been used for validating the EM solver and presented in [3]. In the present case, the objective is not so much to compare against the experiment but to ensure that the beam keeps a consistent behavior when modelled with solid elements (the classic way) or with shells elements (the new way). Results for the beam's oscillations are shown of Figure 3 and Figure 4. As one can see the results are very similar for the two methods. A slight phase difference can be observed the reason for which is unknown at this time which may be due to the different mechanical behavior of shells and solids.
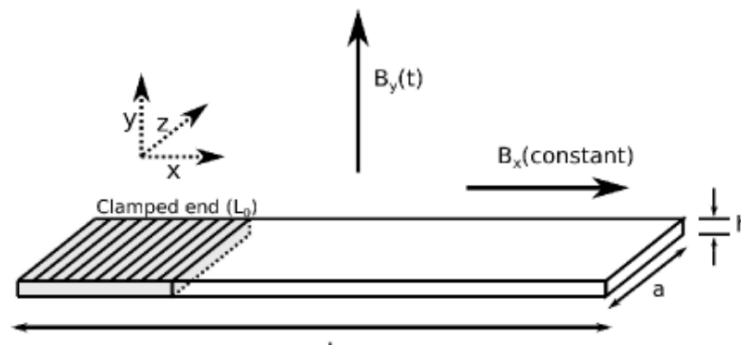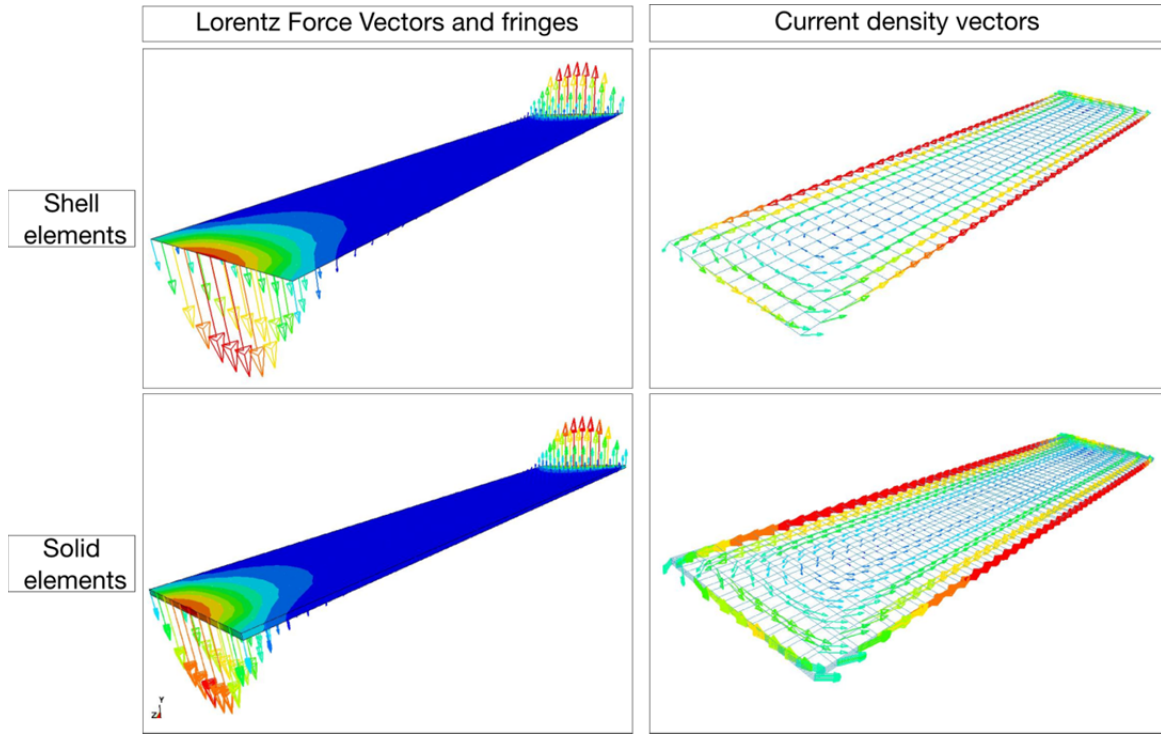

Figure 2 Sketch of the TEAM12 problem

Figure 3 Visualization results for the TEAM 12 problem. Comparison between using shells or solids for the beam.
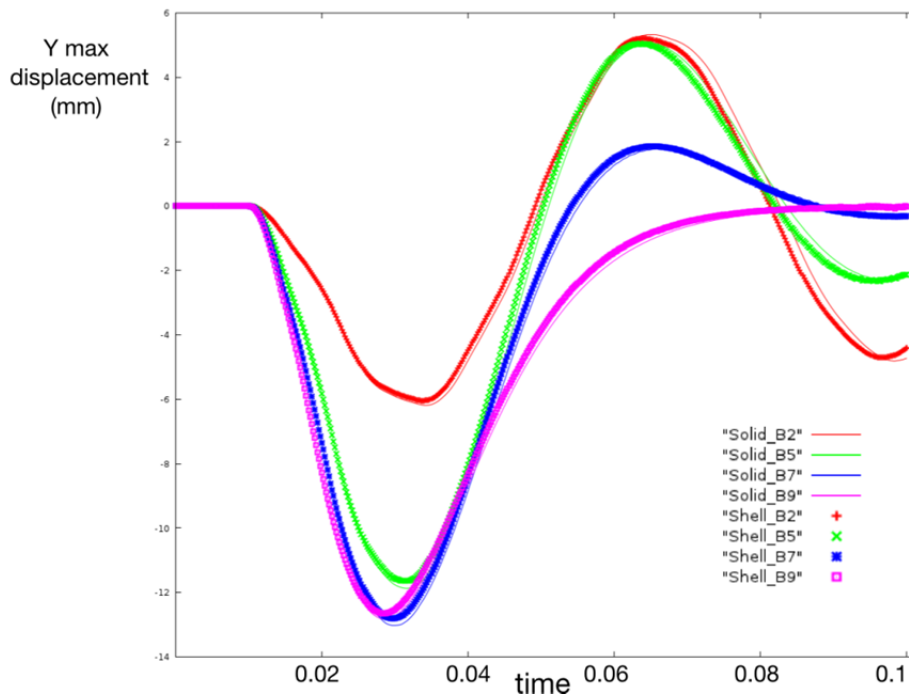

Figure 4 Maximum beam displacements for different Magnetic flux amplitudes (0.2, 0.5, 0.7 and 0.9 T) [2].

Illustration on a typical metal forming case

We now present a typical magnetic metal forming simulation using shell elements. The simulation represents the free forming of an aluminum plate by a spiral coil and is very similar to the case presented in [1]. Comparison is again made against the equivalent solid element case. It appears clearly on Figure 5 that both behaviors are similar and consistent. When looking into more details, some small differences can be observed but those can be explained by the fundamental and intrinsic different characteristics of shell and solid elements on the structure side, since this case presents very large deformations.
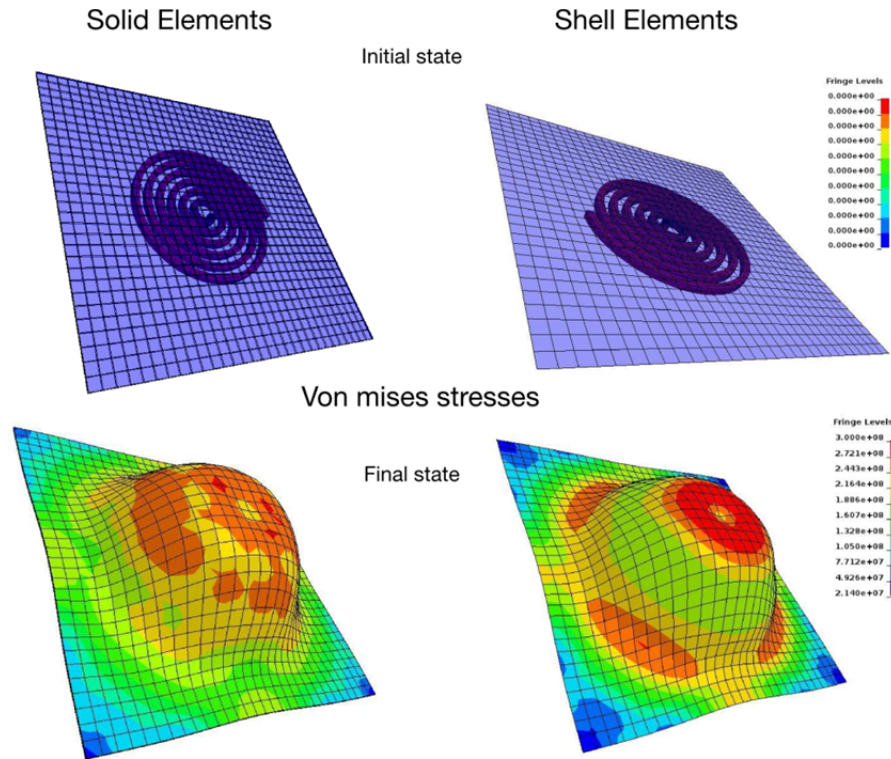

Figure 5 Results for the forming test case. Comparison between using shells and solids for the workpiece.

Update and future developments on shells for EM

The EM solvers 1 (Eddy Current) and 3 (Resistive heating) are now coupled with shells, soon to be extended to solver 2 (Inductive heating). One can combine shells (e.g. for the workpiece) with solid elements (e.g. for the coil). This works in SMP and MPP. More options may be added for the through thickness distribution of the solids in order to better represent the skin depth.

Magnetic field lines in the air

A new feature has been implemented in order to display magnetic field lines at a given time in both the conductors and the surrounding air. This feature is important since the use of the BEM method does not allow the visualization of the EM fields in the air. However, it does not change anything in the way the EM fields are solved; those field lines only aim at giving visual additional information to the user. Consequently, a new card has been added, *EM_DATABASE_FIELDLINE which can be used to trigger and control the calculation of these field lines.

Basically, the user needs to provide one point which will be used as a starting point for the field line. He also needs to specify how many points he wants on the field lines and the frequency of computation of these lines. There are two optional cards. The first one allows the user to define the type of integration scheme used to compute the lines (Runge Kutta 4 or Dormand Prince 853) [4]. The other one allows the user to define the method used to compute the field B which is the second member of the field lines equations.

One has to be aware that the computation of the magnetic field lines could be time consuming especially when some points are close to the structure. What actually drives the cost of the magnetic field lines computation is the calculation of the second member. The direct method is accurate but shouldn't be used systematically. Two methods of approximation are available: the multipole method [5] and the multicenter method. The latter one has been developed at LSTC.

Calculation methods

Integration scheme

The magnetic field lines are useful for visually representing the strength and the direction of the magnetic field $B(x)$ where $x \in \mathbb{R}^3$ is the coordinates of the field line. By definition, those lines are tangent to the magnetic field in every point and are defined by the following differential equation system:

$$\frac{dx_i}{ds} = \frac{B_i(x)}{|B(x)|} = \widehat{B}_i(x) \text{ with } i = 1,2,3$$

Here we are interested in the geometrical properties of $B(x)$ frozen in time. Therefore, s should not be interpreted as time but as the path length along the field line.

Those equations are solved using an explicit Runge-Kutta integration scheme, either Runge Kutta 4 or Dormand Prince 853 [4].

Method to approximate the 2nd member

There are two cases when it comes to compute the magnetic field B on one point which will be called the target point. Either the point is inside the conductors which generates the magnetic field and therefore the computation of the magnetic field directly comes from the FEM solution or the point is outside the conductors and the magnetic field is given by the Biot-Savart law [6]. To evaluate the contribution of the charge distribution (represented by the structure) which is confined in a finite volume on a target point outside this volume, the direct method simply sums

the contributions of all the source currents inside the conductors. This is often time consuming. However, one could also use the fact that the target is often far away from the charge distribution to compute an approximate contribution rather than the exact one. Based on this idea, two methods, the multipole and multicenter methods are currently being investigated. More information on the multipole method can be found at [5].

Examples

Torus

Let's consider a torus in which one an electric current circulates which generates a magnetic field B around it. The torus is split into 900 solid elements. The magnetic field lines are shown on Figure 7.
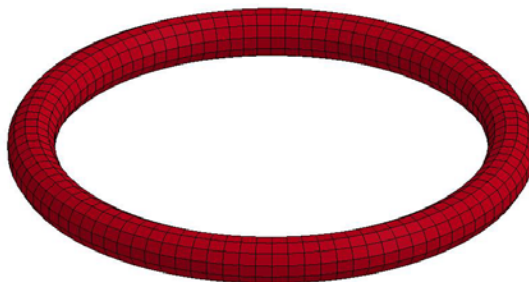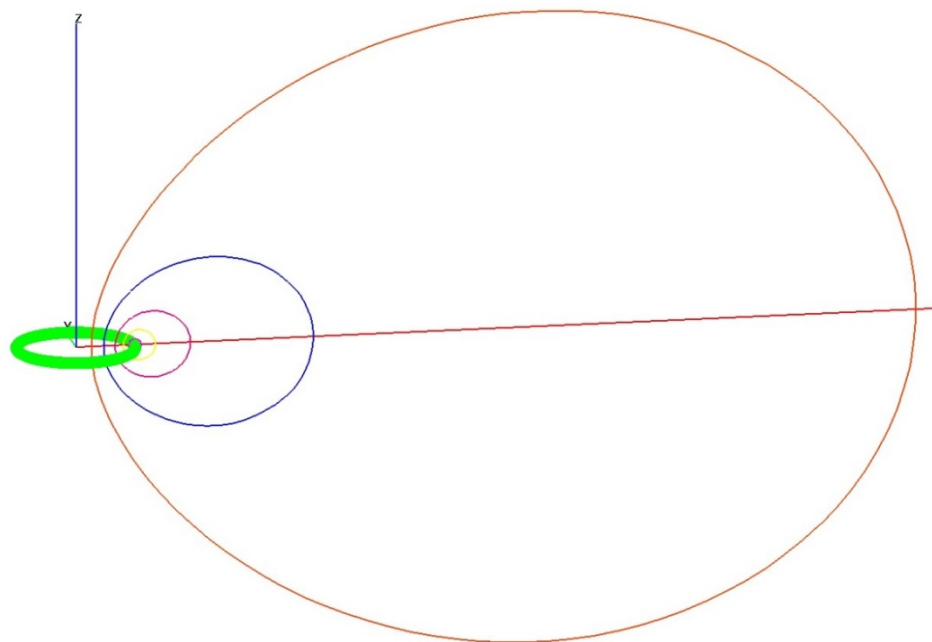

Figure 6 Torus mesh

Figure 7 Magnetic field lines for the torus case

Time performances:

Method	Initialization time	Computation time	Total computation time
Multicenter	13s 24ms	68ms	13s 92ms
Multipole	1s 54ms	1s 22ms	2s 76ms
Direct	-	-	3mn 30s

Coil sections plus Plate

Let's now consider the section of a coil plus a plate. This could represent part of an MMF simulation (See Figure 8). An electric current circulates into the 3 tubes which induces a current in the plate. An electromagnetic field turns around the 3 tubes and is compressed around those tubes due to the plate. The tubes and the plate are split into 13005 solid elements. The magnetic field lines can be seen on Figure 9.
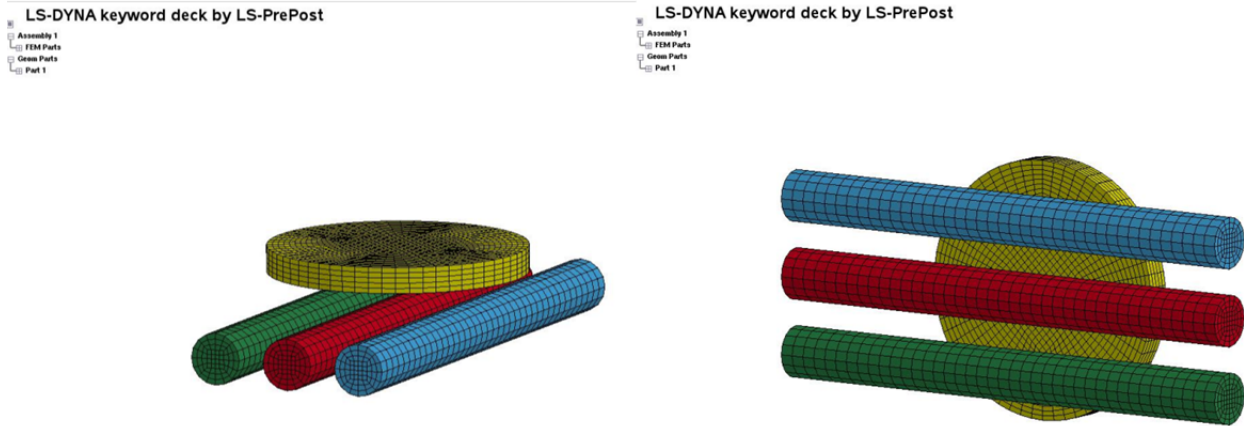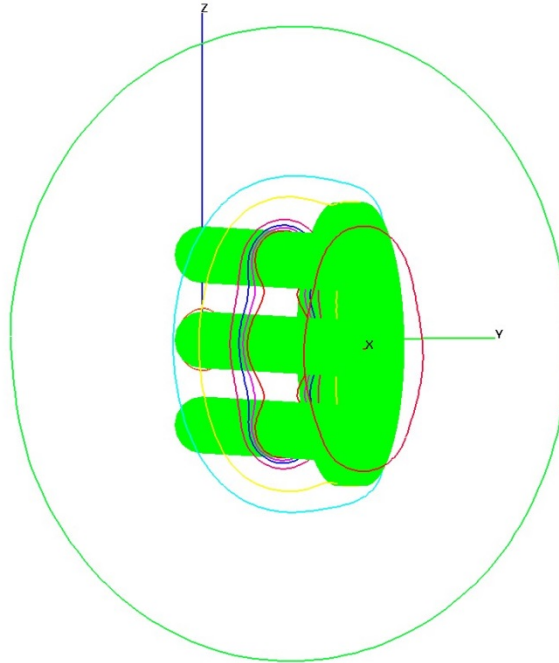

Figure 8 Mesh of the coil plus plate case

Figure 9 Magnetic field lines for the coil plus plate case

Time performances:

Method	Initialization time	Computation time	Total computation time
Multicenter	13smn 11s	35s	13mn 46s
Multipole	22s	1mn 19s	1mn 41s
Direct	-	-	6h 31mn

Conclusion and future developments on magnetic field lines

As can be observed from the previous tables, the advantages of the multipole and multicenter methods versus the direct method are evident regarding computational time. Further research will be undertaken on those two methods which, if proven successful, could be used during the assembly of the BEM matrices and maybe the solution of the BEM system thus reducing the computational time of the whole EM run.

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