Multi-scale Modelling in the Time-Domain for EMC Studies

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Abstract

The paper addresses a particular feature of EMC, namely the presence of multi-scale objects, which make it a very challenging modelling problem. By a multi-scale problem we mean the presence in the same solution space of features which are electrically small (relatively to the wavelength) and electrically large. The "brute force" approach requiring as it does increasingly faster and larger computers has its limits. What is needed is an innovative modelling approach which employs hybrid techniques to maintain acceptable accuracy and modest computational demands. In this paper we focus on two approaches. First, the embedding of local solutions around fine features in the form of macro-models. Second, the hybridization of structured and unstructured meshes to facilitate feature description and adapt spatial resolution to local conditions and requirements.

1. Introduction

The modeling and simulation of problems in EMC is an extremely challenging application for computational electromagnetics (CEM). Although, in most cases, the accuracy required is not very high, the difficulty comes about from the extreme complexity of practical systems and the wide frequency range over which characterization is required [1]. Three dimensional modeling in the time-domain requires a spatial sampling at least as fine as $\lambda/10$, where λ is the wavelength at the highest frequency of interest. Taking as an example an upper frequency of 1GHz the spatial sampling in free space must be finer than 3 cm. In practice, the upper frequency limit for EMC studies is much higher (an order of magnitude higher is typical) thus requiring a resolution of the order of a few mm. This in itself leads to very intense computation when the problem to be simulated is larger than a few wavelengths. The memory demands increase alarmingly with electrical size and, since the time step in explicit schemes is related to space resolution and propagation velocity, run times increase rapidly. All this is uncomfortable, but there are further problems when one is confronted with the so called multi-scale problems [2]. The term describes the presence in the same problem of features with widely different electrical scales. An example is a problem which say is ten wavelengths large in each direction with $\lambda/10$=3cm (10^6 cells) containing a feature say a wire with diameter 1mm. Whilst a spatial resolution of 3cm will deal comfortably with simulation up to 1GHz it cannot directly resolve the geometrical detail of the wire diameter. Attempting to refine the resolution say to $\lambda/20$ still does not help with the wire whilst increasing computational demands eightfold. This type of problem is very common especially in EMC problems. A number of approaches are possible short of increasing resolution to unacceptable levels. One approach is to retain the resolution to $\lambda/10$ thus keeping within reasonable computational demands and then embed suitable macro-models describing local behaviour near the fine feature (the wire in our example). Another approach is to distort the mesh locally near the fine feature to increase local resolution to a degree which is adequate for certain problems (e.g. curved boundaries). In practice, both approaches are useful and the particular choice is strongly problem depended. In this paper, the rationale behind each approach, its pros and cons, are briefly described to help practitioners approach practical problems and to point to the needs of future development.

2. Macro-models

The idea of embedded structures, also referred to as sub-cell models, appears to be a reasonable one. The rationale is based on the observation that very near a feature the solution is strongly dependent on the local environment and is less dependent on global conditions. Hence, if somehow a local solution is obtained and interfaced to the mesh very close to the feature an efficient and accurate model is obtained. The first significant development in this area was the embedding of wires and struts into an FDTD mesh [3]. Here in essence, the quasi-static solution around the wire is interfaced to the surrounding mesh i.e. we exploit the fact that the electric charge and current (wire quantities) and electric and magnetic field (quantities mapped on the mesh) are related through the well known expressions $E=Q/2\pi\varepsilon r$ and $H=I/2\pi r$. The radial distance from the wire axis where this embedded model is interfaced to the mesh is of the order of $\Delta/2$ where Δ is the mesh resolution (cell size). Several models where based on this work including a sophisticated multi-conductor model for TLM [4, 5] and FDTD [6]. It is interesting to consider the degree of innovation shown by modelers in exploiting this model

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to tackle increasingly more challenging problems. Extensive work in dealing with junctions and bents has been done in recent years. The nature of the quasi-static solution is that it possesses cylindrical symmetry. So at the mesh sampling points which are at the edge of the cell it is difficult to model situations where the embedded feature (wire) is placed off centre relative to the centre of the cell. This is one limitation, which however leads to another. If more than one wire needs to be embedded into a single cell (multi-wire bundle) then in effect all the wires are co-located thus introducing timing errors. These may be negligible at lower frequencies but their impact is felt in more challenging applications e.g. HF signal integrity studies. In a further development, the embedded wire model was refined by improving the local solution around the wire of radius a beyond its quasi-static limitations to include more solution modes [7, 8].

$$E_z(r,\varphi) = \sum_{n=-\infty}^{\infty} B_n e^{jn\varphi}[J_n(k_c r) - \frac{J_n(k_c a)}{N_n(k_c a)} N_n(k_c r)]$$

The idea is simply illustrated in 2-dimensions where information about the embedded object at the centre of the cell is sampled at the four points at cell boundaries as shown in Fig 1. The normalized modal amplitudes are also shown.

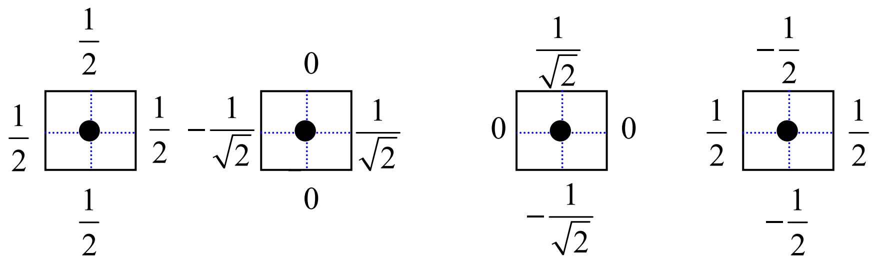

Fig 1 Schematic of four modes used for decomposing fields at the four sampling points in 2D

In this approach we have included as many modes as possible (4 degrees of freedom). The relative strength B_n of each mode allows for calibrating the position of the wire inside the cell. Information about the embedded object (wire) is encoded into the impedance seen by each mode at the sampling points (surface of the cell). The basic strategy is to decompose into modes signals from the mesh impinging on the cell boundaries containing the wire, scatter each mode according to the properties of the wire, then from the scattered modes reconstruct the total signals reflected from the cell containing the wire and pass on to the rest of the mesh. Thus the mesh resolution can be set on the basis of global considerations (e.g. $\lambda/10$) but much finer embedded object may be incorporated at a minimal computational cost. The key to this approach is to obtain the modal components of the solution for the embedded object. In the example given here the solution for a long cylindrical wire is well known so it is straightforward to construct the modes. In other cases this may be more difficult or impossible analytically. In such cases the modal solutions may be obtained numerically by pursuing the solution in two steps. First, a numerical study is first done to model a single cell with the embedded object using a very fine mesh to resolve all relevant geometrical details. This furnishes the modal components. Then the full numerical study is done where the cell with the embedded object, described in terms of its modal scattering characteristics, as a part of a large mesh modeling the entire problem space. Thus the large problem computation is done without delving into the details of the embedded object which is however efficiently and accurately described by its modal properties. Several papers address such developments including, offset wires [8], multi-wire bundles [9], slots and thins strips [10], generalized embedded objects [11] and wires embedded in 3D [12].
Another approach for embedding multi-scale objects into a mesh is based on the characterization of its scattering properties in the frequency domain and the derivation of, in essence, an equivalent digital filter (DF) which represents a procedure in the time domain that can be directly interfaced to the rest of the TD model. The nature and complexity of this filter depends on the properties of the object to be embedded. A systematic approach starting from the FD characteristics, extracting the poles and zeros of the scattering coefficients representing the object and applying the bilinear transformation gives a procedure in the z-domain [13] which is then embedded in the TD mesh procedure. In most cases a small number of poles is sufficient for adequate characterization and since the embedded objects are only a small fraction of the total problem space the computational overhead is a very modest one. The spatial and temporal parameters of the mesh remain unaffected and chosen for efficiency and global accuracy. This powerful approach has been applied to the modelling of complex materials [14], conducting panels with fine perforations [15] and the modelling of meta-materials. In this case large panels covered with meta-materials, which consist of intricate designs, are replaced in models by DFs which describe their essential behaviour at very modest computational cost.

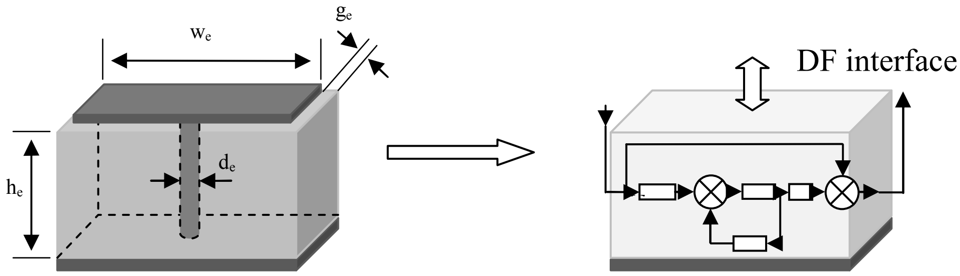

Fig 2 Schematic of an EBG element (left) and its digital filter representation (right)

An example is shown in Fig 2 (left) of an EBG device used to modify the reflection properties of a conducting wall. Some of the geometrical details (g_e, d_e) are fine and direct meshing down to this detail is computationally extremely expensive when the device is just one element of a large problem space. The schematic on the right shows how the EBG configuration is replaced in a model by a DF with parameters obtained from the frequency characterization of scattering from the basic cell, extraction of poles and zeros and application of bilinear transform. Details of this process for the EBG and for efficient absorbers made out of cut wires may be found in [16].

3. Hybrid and Un-structured Meshes

In the last section an approach was described where the mesh remains unaltered and any problematic structures are embedded through suitable macro-models. However, there are situations where altering the structure of the mesh is beneficial. A well known example is the modeling of curved boundaries where a Cartesian mesh results in stair-casing errors. This is shown in Fig 3 (a) where a mesh based on triangular cells is also shown (b) and it is seen that it is capable of approximating better the curved boundary.

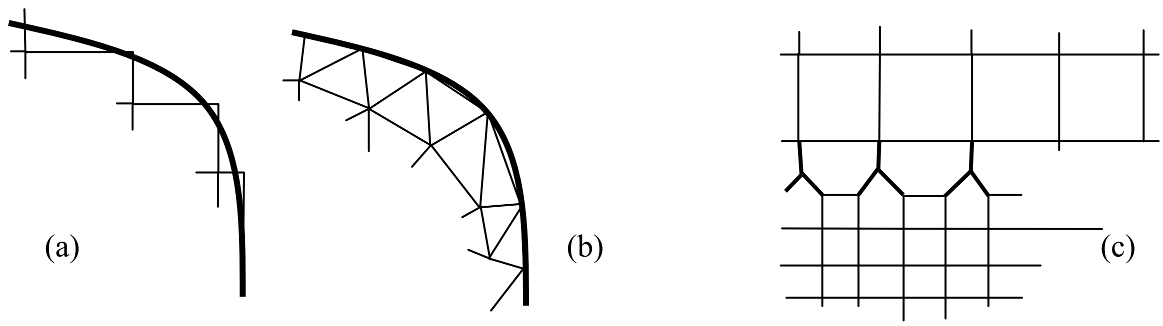

Fig 3 Staircase approximation on a curved boundary (a), unstructured mesh (b) and hybrid mesh (c)

A regular Cartesian mesh is by far the most efficient both in terms of design and computation. However, an unstructured mesh, where the number of cells around each nodal point varies according to the needs of the problem, offers greater flexibility but at significant computational cost. The basic element of a general unstructured mesh in three-dimensions is the tetrahedron. A problem meshed entirely with tetrahedra, would in general have a large number of different shaped elements, thus requiring calculation and storage of different parameters for each cell (several million cells are typical). A further issue which is important for general unstructured meshes is their quality. Issues such as whether the mesh is Delauny compatible are well known when applying techniques such as finite elements. In time domain, the shape of each element must be such that the time-step is not too small which again implies that long and thin elements are undesirable. If some sides are very short they result to very short time-steps and very inefficient calculation. Hence, a general indiscriminate use of an unstructured mesh, in spite of its flexibility, is not an obvious or easy choice for general 3D calculations in the time-domain. Reflecting on these issues one is compelled to conclude that the best choice is a hybrid mesh where each section of the problem space is modeled using the most appropriate mesh. This may mean that for some parts a regular coarse Cartesian mesh is selected, for other parts a finer Cartesian mesh is the best choice and for selected areas (e.g. near curved boundaries, intricate features, or for stitching together different areas of the mesh) an unstructured mesh based on tetrahedral elements is preferred. This is shown schematically in Fig 3(c). Significant work in this area has been done and is of continuing major interest as can be seen in [17] and references quoted there.

4. Conclusion

Some of the approaches to multi-scale modelling in the time-domain were described. These are based on embedding suitable macro-models derived from local solutions, digital filter algorithms, or distorting the mesh to form suitable hybrids of structured and unstructured parts. Significant further work is required to establish comprehensive and efficient libraries of macro-models and general approaches to hybridization to measure up to the challenges of CEM for EMC applications.

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