THE EU FRAMEWORK V PROJECT “GEMCAR”: PRACTICAL ASPECTS OF THE DEVELOPMENT OF WHOLE VEHICLE ELECTROMAGNETIC MODELS

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Abstract: Even when suitable CAD data, modelling tools and computing resources are available, many practical difficulties and limitations remain for engineers attempting to build electromagnetic models of complex systems such as vehicles. This paper discusses practical issues concerned with the development of whole vehicle electromagnetic models, including the acquisition and processing of CAD data, identification of vehicle components that could be neglected from numerical models, and computational issues.

1. Introduction

There is a considerable gulf between the availability of a 3D field modelling tool and the ability to build successful electromagnetic models of vehicles. In fact the detailed geometrical models of vehicles that are needed in order to build an acceptable discretized representation of the vehicle are only now becoming widely available. Furthermore, the computing resources that are needed to solve such models over the frequency ranges of interest, and in a time that is acceptable for industrial purposes, have only recently become affordable for more than a handful of potential users.

However, even when suitable CAD data, modelling tools and computing resources are available, many practical difficulties and limitations remain for those attempting to undertake computational electromagnetics (CEM) for complex systems such as vehicles. The process for CEM modelling, using any technique, comprises three main phases:

- pre-processing – in which a description of the geometry of interest is prepared for the specific simulation technique;
- simulation – in which the response to a specified excitation is computed;
- post-processing – in which the simulation output is worked into a form that is amenable to analysis.

This paper discusses a number of practical issues relating to the construction of vehicle electromagnetic models, including CAD import and meshing for EM modelling tool, essential model content and computing issues.

Many of the practical difficulties that are encountered are generic, but some are also specific to particular types of modelling techniques. Consequently, the range of numerical methods that were used in the GEMCAR project was selected to be representative of the full range of techniques that are currently available.

2. Vehicle CAD import and meshing

There are modelling applications for which detailed representation of a specific vehicle is not necessary. For the investigation of particular vehicles, however, it is essential to have access to CAD geometry in order to develop an adequate electromagnetic model. Although many of the issues relating to CAD import and meshing are common to all numerical methods, some aspects are inevitably specific to particular techniques or groups of techniques. Both of these types of issue are outlined below.

2.1 Common issues

The first problem to be resolved in building electromagnetic models is to acquire geometrical data for parts that are of interest. A typical geometrical model for a vehicle is constructed from many thousands of sub-assemblies and lower order parts, most of which will not be of interest for electromagnetic models because they are either too small to be important or the materials from which they are formed are unlikely to be significant. A preliminary filtering scheme that allows the unwanted parts to be rejected is desirable, and probably practicable, but would require the CAD database to be structured in a manner that would support the needs of this process. At present, however, this preliminary filtering normally requires manual inspection to identify parts that can be discarded (such as nuts, bolts, screws etc.).

A second stage of filtering is then required to identify which of the remaining parts can be neglected, perhaps because their surfaces are either coincident with or contained within other parts, or because they are not expected to be significant for the model application. An example of the latter could be a model intended for examining the fields inside the passenger compartment, for which the components inside the engine bay and underneath the bodyshell are not likely to be significant. It is not easy to see how this type of filtering could be automated, as it depends on the intended purpose of the model and the judgement of the analyst. Some aspects of the rationale for including or rejecting some of the larger components are discussed further in section 3 below.

After the geometrical data has been collated it is necessary to define a suitable meshing strategy, which meets the requirements of the selected numerical technique and the modelling application, and then impose this scheme on the geometrical model in order to obtain the discretized model needed to carry out simulations using the desired 3D field modelling technique.

An automated meshing algorithm generally requires coherent and unambiguous 3D geometry in order to generate a mesh successfully. This requirement, however, is not always easily satisfied. The main causes of problems with geometry include:

- poorly constructed geometrical models (3D models may that appear correct when drawn, but are not properly connected, contain duplicate entities etc.)
- defects introduced through translation (an intermediate file format is often needed where different tools are used for meshing and drawing), which may occur during both export and import
- geometrically complex features that the meshing algorithm cannot cope with

Poorly constructed models and overly complex features can be corrected, and many CAD products provide geometry repair tools to assist with this. The potential for corruption and incompatibility in data interchange can only be resolved through the use of intermediate geometry repair tools that can provide geometry that is acceptable for the meshing algorithm. These problems also afflict the more established automotive modelling disciplines, but are perhaps more acute for computational electromagnetics because much more of the vehicle geometry is required for these purposes. Thus, it is not currently possible to obtain all of the required geometry in a suitable state of topological integrity, and it is often found that CAD is not available for all of the parts that are required.

The ideal situation would be a unified process in which the CAD data is repaired to the point where it can be used as source material for any kind of numerical modelling, thus allowing suitable meshes to be derived directly from CAD with minimal manual intervention. In practice, the complexity of the problem is such that this is often not practicable, and considerable effort, often requiring several different software tools, remains necessary.

Although CAD is in many ways the most satisfactory starting point for mesh generation, it is also possible to use mesh data intended for other modelling disciplines (such as crash or aerodynamics models). It is not uncommon to find that, while there may not be CAD data for all vehicle parts, there are finite element meshes that have been manually generated for other purposes. It is possible to regenerate geometry from such meshes that can be used for further meshing. It is also possible to re-mesh the available mesh directly. The latter approach can be quicker than meshing directly from CAD, since the surfaces are already considerably simplified and the topological integrity of the existing mesh is guaranteed. It is expected that this type of approach will become more common in the future as re-use offers vehicle manufacturer the opportunity to extract the maximum value possible from their existing investments in CAD processing and mesh generation activities

These problems are not usually apparent in the simple examples that are normally demonstrated by software vendors. For a real vehicle, however, the number of surfaces to be processed will be $\sim 10^5$, which can take a considerable amount of time to process (perhaps even days) if the model is required for use at the low microwave frequencies that are now becoming of interest. Robust meshing algorithms, which will not fail as soon as they encounter the first topological ambiguity, are essential to treat CAD data of real-world complexity. The problem areas in the geometry may in fact only affect a very small proportion of the total mesh, and small spurious holes and missing parts can probably be tolerated without adding greatly to the existing model errors. Much greater approximations will almost certainly have already been introduced in order to make the development of the model practicable.

Where CAD data is available for the wiring harness, it is likely to be in the form of a 3D tube representing the path and diameter of the bundle, as well as associated features such as branches, connectors and mountings. However, this data is not sufficient for CEM models. The path data is useful for both integrated and separated cable models (for the latter the field along the harness path is obtained from 3D field models for use as input data for cable network models). Modelling the cable response requires further information, concerning the position of wires in the bundle, as well as their dimensions, material properties and termination impedances. This type of information is currently less readily available, and is subject to much more uncertainty than the vehicle geometry.

2.2 Particular issues

The numerical methods that were represented in the GEMCAR project included:

- boundary elements (BEM) in frequency domain;
- finite differences in time domain (FDTD);
- finite volumes in time domain (FVTD);
- method of moments (MoM) in frequency domain;
- transmission line matrix (TLM) in time domain.

In terms of the field modelling methods that are currently available, this list is fairly comprehensive but is by no means complete. However, the problems with these methods can be considered in terms of whether a body fitted mesh is used.

For surface meshing techniques, such as BEM, MoM and FVTD (which, like finite elements, requires a surface mesh to "seed" the unstructured volume mesh), the mesh reflects the topology of the surface, as illustrated in Fig. 1 below. However, the computing requirements for the model increase very rapidly with the number of elements (and hence the number of surfaces) that are included in the model. Thus there are significant advantages in pre-processing the geometry to minimize both the number of surfaces and their complexity.

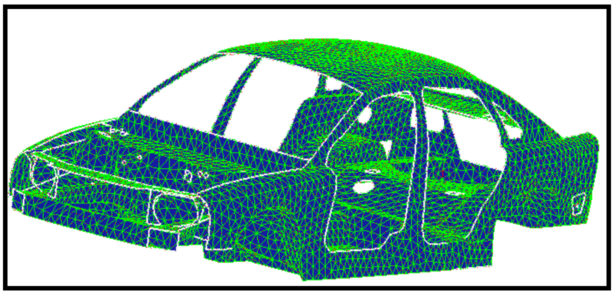

Fig. 1: Surface mesh for a vehicle bodyshell derived from simplified CAD data (both generated by EADS)

For volume meshing techniques based on a structured mesh (such as TLM and FDTD) the number of surfaces to be meshed has no impact on the computing requirements for the model, which are determined essentially by the cell size and the volume of space that is to be modelled (ie. by the total number of cells in the model). Thus, while there may be some merit in simplifying the surfaces (depending on the capabilities of the meshing algorithm) there is no advantage in limiting the number of surfaces.

The main disadvantages of this type of approach is that the resulting model employs a “stair-cased” approximation to curved surfaces (see Fig. 2) and the finite volume of the model has to be truncated using some form absorbing boundary condition (which in practice will generally give rise to spurious boundary reflections).

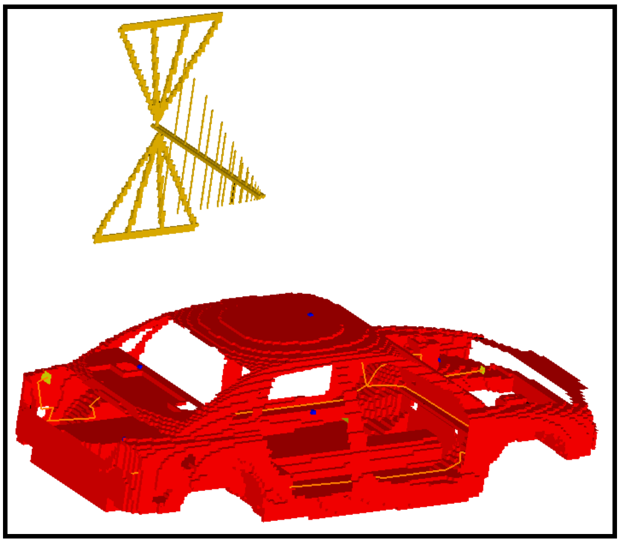

Fig. 2: TLM mesh for simplified bodyshell (with integrated harness model and vertical biconilog antenna at side)

Thus, the surface meshing techniques are able to provide a body fitted mesh, but their ability to represent both the exterior surfaces (which determine the scattering from the vehicle) and the interior surfaces (which determine the internal resonances) is more limited. By contrast, the volume meshing techniques based on structured meshes can accommodate both the interior and exterior surfaces at negligible additional computing cost, but do not provide a smooth representation of these surfaces.

3. Vehicle model content

A complete model containing all parts of a vehicle is unlikely to be practicable for the foreseeable future due to the resulting model complexity and computing requirements. In addition, in many cases it may not be possible because the detailed geometry may not be available at the time that the model is required. Consequently, it is necessary to establish which parts of the vehicle must be present in the model in order to ensure that an adequate representation of the characteristics of the real vehicle can be obtained.

It seems reasonable to assume that many of the smaller items that are found in a complete vehicle, such as brackets and fixings, will have negligible impact on the electromagnetic characteristics. The vehicle can then be considered in terms of the following major groups of components, as follows:

- bodyshell (ie. chassis and metallic body panels);
- window glazing and associated parts;
- seats (largely metal frames with foam mouldings and leather or textile coverings);
- interior trim (carpets, instrument housing, plastic parts) and composite elements (eg. body panels);
- mechanical parts (engine, powertrain, suspension, brakes, tyres, brake pipes, exhaust etc.);
- electrical parts (ie. harness, modules and antennas).

The likely significance of these types of components for electromagnetic models of vehicles is discussed below.

3.1 Bodyshell

The main bulk of the body shell is the most fundamental element of the model. The outer surfaces will determine the scattering characteristics of the vehicle under external illumination, but the interior surfaces, which can be significantly displaced from the outer surfaces ($\Delta x \sim 0.1$ m for vehicle doors), will determine the internal resonances of the structure. Consequently, both the inner and outer surfaces are required in areas where their separation is significant.

For some applications (eg. installed performance of antennas [1]) it may be necessary to include thin slots around the periphery of vehicle doors. Vehicle body variants (hatchback, estate, convertible etc.) and optional structural features, such as a sunroof, also need to be taken into account in identifying the requirements for the model. Numerical studies [2] indicate that a sunroof may modify the field coupled into the interior of a vehicle by up to around 5 dB, while changes of 10-15 dB are likely in the fields radiated from internal sources.

3.2 Window glazing

Vehicles contain a large number of windows to ensure good driver visibility, but these features also provide significant field coupling paths between the interior and the environment. Moreover, it is increasingly common to add components such as heaters, antennas and solar screening to vehicle glazing.

3.2.1 Simple glass windows

Although glazing materials have a relatively high dielectric constant ($\varepsilon_r \sim 7$ for typical glasses), the thickness of vehicle windows is sufficiently small to suggest that their effects will be minimal at frequencies up to 1 GHz. Comparative field measurements carried out with the side windows up and down show little difference between these two conditions [3], except in the upper part of the frequency band. However, at frequencies above 1 GHz even simple glazing may become significant for electromagnetic coupling. Theoretical estimates of the reflectance for a dielectric slab under plane wave at normal incidence are illustrated in Fig. 3, for representative single layer and laminated arrangements.

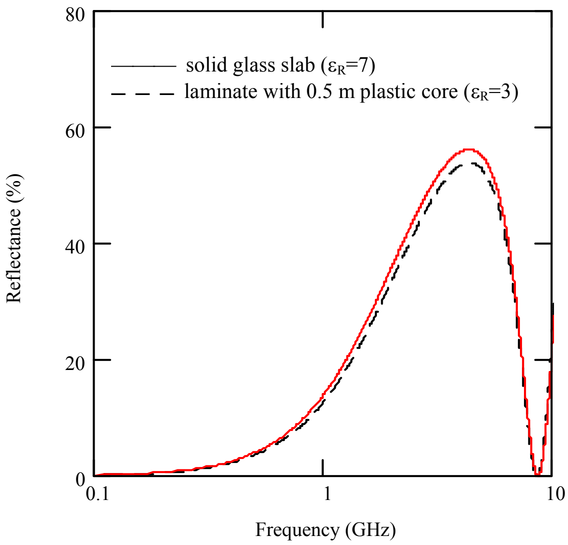

Fig. 3: Reflectance of 6.5 mm thick infinite dielectric slab under plane wave illumination at normal incidence

In general, therefore, it seems reasonable to ignore the vehicle glazing for frequencies up to 1 GHz where simple glass panels (including laminated structures) are present. However, not all windows are of such simple construction, as conductive materials and structures are commonly embedded in the glass.

3.2.2 Heaters embedded in glazing

Embedded heating elements are commonly used in vehicle windows, usually in the form of simple arrays of conductors, to provide a demisting or de-icing function. Almost all vehicles are equipped with a heater for the rear window, usually in the form of an array of horizontal conductors, although more complex arrangements can also be found. A more recent development is the introduction of heating elements into the front windscreens of some vehicles, where a much denser array of fine vertical conductors is often used, which minimizes visual disruption for the driver.

At frequencies for which such arrays are relatively dense, field components that are co-linear with the conductors will be reflected while the orthogonal components will be transmitted. Measuring such effects is also not easy, because of the need to remove fixed glazing, but a representative numerical model can be used to assess the potential impact of such structures on vehicle emissions and immunity performance. However, numerical results [4] for typical heater geometries indicate that a windscreen heater has a more significant impact that a rear window heater and that the impact on emissions is greater than for immunity. It is also found that under illumination from the front of the vehicle, the field in the interior is predominantly vertical for both horizontally and vertically polarized sources. The effect of the rear window heater is therefore likely to be greater for horizontal illumination from the rear of the vehicle.

3.2.3 Antennas embedded in glazing

Security and styling considerations, as well as the increasing numbers of antennas deployed on vehicles, make conformal designs increasingly attractive for automotive applications. These are often embedded in the window glazing, and are commonly integrated with the rear window heater array. Another location that is sometimes used is behind composite bumpers.

At high frequencies the local dielectric material be significant for the performance of such antennas, but even at low frequencies ($f \sim 100$ MHz) where the material is electrically thin the effective dielectric constant is sufficient to modify the electrical length, and hence the performance characteristics, of the antenna. This effect has been shown by experimental methods [5] at VHF frequencies and in numerical models of an antenna at DAB (digital audio broadcast) frequencies [6]. Thus, the presence of the dielectric cannot be simply neglected in attempting to predict the installed performance characteristics of such antennas.

3.2.4 Solar screening

In some cases conductive material is added to the glass in order to reduce the transmission of solar radiation (infra-red and ultra-violet) into the vehicle interior. Such schemes are implemented by doping the glass, by adding surface or embedded coatings, or by including a meshed structure. The latter is commonly used in sunroof glazing, while some laminated windscreens contain an embedded metallic layer.

There is some anecdotal evidence to suggest that this type of solar screening may also influence the transmission properties of the glass at the lower frequencies of interest for EMC performance. However, it has not been possible to address these issues within the scope of the GEMCAR project.

3.3 Vehicle seats

Vehicle seats are normally constructed from a metal supporting frame, stiff plastic parts, shaped foam and a thin covering of some type of textile or leather. The rear seats are often of much simpler geometry than the front seats. The rear seats generally obtain their rigidity from the floor pan and a simple metal panel between the passenger cavity and the rear luggage space. The cushions are therefore largely shaped foam with very little metallic content (perhaps some wire stiffening adjacent to the metal panels). Their electromagnetic significance is therefore likely to be smaller than that of the front seats.

The front seats, by contrast, are much more complicated. The seat itself must provide rigidity for the user, including headrests, and numerous adjustment mechanisms are provided to maximize comfort. In addition, the seat may be fitted with heaters, motors, and even systems for assessing the mass of the user. Airbag modules are also found embedded in seat structures. The back of the seat is often constructed from a stiff but open frame, with thick wires running across the open central area to provide support. It would seem likely, therefore, that the front seats would have a very significant impact on the electromagnetic characteristics of a vehicle.

Measurements of the field coupled into the region above the rear seat with and without the lower rear seat cushion in place indicate that this structure makes very little difference [3]. This suggests that all such foam and fabric structures within the vehicle can probably be neglected.

Although there are differences between the field and wire coupling results obtained with and without the seats, the impact of these structures is generally much smaller than expected. It appears that a model without the seats would give a good guide to the fields that would be seen above the seats and current levels that would be induced on harness elements running along floor pan adjacent to the doors. This suggests that even the front seats could be neglected in automotive CEM models for many applications. Nonetheless, they will be essential in models that aim to predict effects in areas that are either within or at least in very close proximity to the seat frames.

3.4 Interior trim and composite panels

The observations noted above concerning the impact of seats and window glass suggests that much of the interior trim of a vehicle can probably be neglected in vehicle models. Much of the plastic used inside vehicles is thinner than the window glass and is likely to have a smaller dielectric constant ($\varepsilon_r \sim 3$ for many such materials). Similar arguments probably apply composite body panels and bumpers, provided that antennas are not associated with such parts.

3.5 Mechanical components

Many major mechanical components represent large conductors, but their locations are such that their influence is likely to be rather limited in many modelling applications. The majority of the wiring harness and the electronic modules are located around the periphery of the passenger compartment, with some in the engine bay and rear luggage space.

There are often sensors and actuators, and therefore harness elements, associated with the braking system and perhaps even the suspension elements if the suspension system is active.

Nonetheless, this represents a relatively small proportion of the total and the bodyshell and doors will provide some degree of isolation between the interior cavities and these under-body components.

The engine bay is packed with mechanical components of many kinds, including metal pipes, and also houses some of the key electrical components. The latter may include engine management systems in internal combustion vehicles, or electric motors and power conditioning electronics in electric vehicles. The associated wiring harness elements may also not meet the criteria for exploiting transmission line models in this area. The engine bay is therefore likely to present a significant challenge for electromagnetic models.

For models where the focus of interest is in the passenger compartment, most of the major mechanical components are probably of little importance except those associated with the steering column, which is inside the passenger cavity, and brackets and members that support the dashboard and instruments.

3.6 Electrical components

Including all of the electrical components in a single monolithic simulation is not practicable. It is possible to treat some elements separately, such as the harness and the modules, but this is unlikely to be the case for antennas, which can be significantly influenced by the vehicle geometry.

3.6.1 Antennas

The installed performance of antennas can be profoundly influenced by the geometry of the vehicle. Such effects are very difficult to predict on the basis of simple arguments, but can significantly impact on system performance. Numerical models suggest that, even for very simple systems (ie. a monopole on the roof of a vehicle) the performance characteristics vary depending on where and how the antenna is mounted [8]. An electromagnetic model of the vehicle, augmented with representations of the vehicle antennas, is therefore needed in order to predict the installed performance characteristics of vehicle-mounted antennas. While this is relatively easy for traditional monopole antennas, there are considerable practical difficulties in developing suitable models for more sophisticated designs.

3.6.2 Wiring harness

The wiring harness provides an important coupling path between the electronic modules on the vehicle, and between these modules and the external environment. Most automotive EMC problems are found to result from coupling via cables rather than direct field coupling to, or radiated emissions from, the modules.

Although it is possible to use thin wire models to produce an integrated model of the wiring harness in the structure (as illustrated in Fig. 2), there are a number of disadvantages in such models:

- additional mesh refinement may be required in order to place the wire in the desired position;
- there is likely to be considerable uncertainty about the geometry of the harness and its terminating impedances (which may well be frequency dependent);
- for time domain simulations, the presence of additional resonant structures may lead to a significant increase in the time required for the system response to decay.

The impact of uncertainties in the geometrical configuration and termination impedances can be investigated much more easily using transmission line network formalism. As much of the wiring harness is normally routed in close proximity to the conducting shell of a vehicle it meets the criteria for approximation as a transmission line structure, thus allowing separated methods [9] to be used. Using these methods, the results of a limited number of CEM simulations of the structure without the harness are combined with many smaller and faster network simulations [1, 7], thereby offering a much more efficient approach to the treatment of wiring harnesses.

This approach can be combined with any CEM technique, but depends upon the harness being sufficiently close to the vehicle shell for the transmission line approximation to be valid. In cases where these criteria are not met, which is likely to be found in areas such as the dashboard region and engine bay, it may be necessary to treat the harness element as an unintentional antenna, which will then require the harness element to be represented in the 3D field model.

3.6.3 Electronic modules

The functional EMC performance of electronic modules is beyond the scope of the GEMCAR project. A separated modelling approach, with behavioural and circuit simulators exchanging data with electromagnetic models [1], is the most practicable approach for modelling functional EMC performance issues. However, some electronic modules may also modify the field distribution and these effects could be significant in some cases.

Including detailed models of electronic modules within whole vehicle electromagnetic models is not currently practicable because of the resulting computing requirements. Modules that are equipped with a screened enclosure could perhaps be represented using a simple conducting block. However, this is not characteristic of automotive modules. Most are without significant shielding structures, often comprising a single board in a dielectric enclosure, although some may have a substantial heat-sink that could also be approximated using a simple conducting block.

4. Computing issues

This section gives a brief overview of computing issues associated with the simulation and post-processing phases of the CEM process. The exact details of the type work that is involved, and the time that is needed to complete it, depend in detail on the modelling approach that is employed, the nature and scale of the system under investigation, and the capabilities of the hardware and software that are used to support these activities.

Possible generic schemes for undertaking CEM modelling of vehicle immunity issues are illustrated in Fig. 4 below. The basic options to obtain a frequency response are to use either a single time-domain 3D field simulation followed by a Fourier transform step (which normally has negligible computing cost), or to carry out many 3D field simulations at different frequencies. The 3D field models could include integrated cable models and/or field output along the harness path to allow transmission-line network codes to be used. The network calculations will also need to be carried out for many frequencies, and may include multiple runs to investigate the impact of uncertainties and variability in parameter such as termination impedance and cable geometry. Finally, the data from the field models and or network models will need to be collated and prepared for presentation in a format that best meets the requirements of the analysis task.

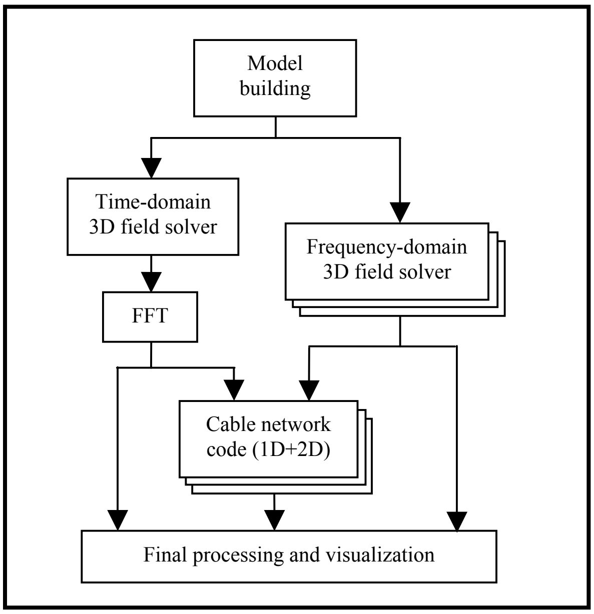

Fig. 4: Options for CEM analysis of an immunity scenario

Of the various tasks indicated in Fig. 4, the 3D field modelling stages will have the longest computing times, greatest memory requirements and produce the largest amount of output data (requiring Gigabytes of disk space if spatial field distributions are requested). Even using high performance computing resources (ie. running in parallel on several processors) such calculations are likely to take hours to complete and require in excess of 1 Gigabytes of memory for frequencies up to 1 GHz. Both the computing time and memory requirements will also increase rapidly with the maximum frequency of interest. In addition, these models would typically need to be repeated under several illumination configurations, representing those commonly used in physical tests (eg. horizontal and vertical polarizations from front and side).

The network models, by contract, require only modest amounts of memory (Megabytes), run in seconds or minutes and produce output files of negligible size. However, if many models are to be run (eg. to derive statistics relating to the variability of harness geometry and termination impedance) then the duration of this activity is likely to become comparable to that for the 3D field simulations.

The volume of data that can result from such calculations is such that information overload is a potential problem that should not be underestimated. Thus, the time that is required to process the results of the simulations into a form that can be absorbed by the analyst and explained to non-specialists can also become a very significant part of the overall computing time.

5. Conclusions

Although an electromagnetic model is not the same as an EMC model, it is an essential element of EMC models. Such a model may also be useful in itself, for assessing EMC risk and installed antenna performance issues during the design stages of vehicle development. In the past, the availability of detailed CAD data, software tools and adequate computing resources severely limited the exploitation of CEM in automotive applications. However, as a result of recent developments in these areas, whole vehicle electromagnetic modelling is now a practicable proposition.

Nonetheless, even when suitable CAD data, modelling tools and computing resources are available, many practical difficulties and limitations remain for engineers attempting to build and interpret electromagnetic models of complex systems such as vehicles. Furthermore, the computing requirements for CEM models at this scale are not insignificant. There are no simple solutions to these problems, but an understanding of model requirements and limitations is essential to enable potential users to build and exploit vehicle CEM models with reasonable confidence in their results.

6. Acknowledgements

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