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Whole Vehicle Electromagnetic Modelling: Developments and Applications

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Author Biographical Notes

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Dean Smythe studied electronics and control systems engineering at Sheffield University and completed a BEng degree in 1994. Mr Smythe joined Ford in 1997 and has worked on the development and analysis of automotive electrical systems for the majority of the subsequent period. Currently working in the Electrical Computer Aided Engineering team he is involved in the application of analytical and computational techniques to electrical systems engineering. A Chartered Engineer and member of the IEE, he is currently studying for an MSc in Automotive Systems Engineering at Loughborough University. He can be contacted at dsmythe@ford.com.

Alastair Ruddle studied physics and mathematics at Bristol University, and completed a PhD in electromagnetic field modelling at Loughborough University. He has carried out research in a wide range of disciplines and industries, but since joining MIRA in 1996 he has been concerned primarily with the development of electromagnetic field modelling techniques for vehicle applications. Other interests during this period include the analysis of EMC and antenna measurement issues, and formal methods for modelling real-time, safety-critical systems. Dr Ruddle is a member of the IEE and the Institute of Physics, and registered as a Chartered Engineer, a Chartered Electrical Engineer and a Chartered Physicist. He can be contacted at alastair.ruddle@mira.co.uk.

Abstract

The electronic complexity of modern vehicles is increasing very rapidly, with the result that traditional test-based methods for validating vehicle electromagnetic compatibility (EMC) performance are becoming inadequate and excessively time consuming. More mature engineering disciplines make greater use of simulation supported by better targeted testing, but electromagnetic modelling of electrically large structures has historically been limited by computer technology. However, recent developments now make it possible to construct and solve whole vehicle electromagnetic models. This paper reviews the electromagnetic simulation tools that are available and discusses practical aspects of developing and verifying vehicle level EMC models, as well as practical examples of how such simulations can be used in vehicle development and validation processes.

1. Introduction

Ensuring electromagnetic compatibility (EMC) performance represents an increasingly significant systems engineering issue for modern vehicles, impacting on their function, safety and reliability. In the past, automotive EMC engineering has been a largely experimental activity, with the result that related activities are predominantly carried out in the later stages of vehicle development. Although testing is also carried out on the sub-systems that are to be integrated into the vehicle, the specifications that must be satisfied at this level cannot guarantee that the installed performance requirements for vehicles [1-2] will be achieved. Consequently, it is really only in whole vehicle testing that potential defects can be detected, and rework costs can be very high at this stage. A further consequence of the traditional approach is that in many cases the sub-systems will be unnecessarily over-engineered, with corresponding cost implications. At the same time, however, manufacturers are aiming to reduce development costs and time to market.

Future vehicle electronic systems will provide many more safety related functions to aid the driver, as well as advanced telematics facilities to support activities such as communications and traffic management. In addition, more sophisticated control systems will be used to optimise vehicle performance characteristics and minimize harmful gaseous emissions. The success of future vehicle technologies that aim to improve transport and to minimize its environmental impact will therefore be critically dependent on the efficient and successful handling of automotive EMC issues. Thus, the advent of alternative powertrain technologies (eg. electric and hybrid-electric vehicles), as well as the increasingly wide range of systems and frequencies that are used in vehicles, are expected to make automotive EMC testing an increasingly onerous burden to vehicle manufacturers in future.

Experience from other disciplines and industries shows that the most effective solution to such problems is to make greater use of analysis and simulation, particularly in the early stages of development where the costs associated with introducing changes are considerably lower than in the final phases of development. Recent developments [3-4] now make it possible to construct and solve whole vehicle electromagnetic (EM) models. It is therefore considered [4-6] that the adoption of numerical modelling techniques is likely to provide the most cost effective approach for future automotive EMC engineering.

2. Electromagnetic Modelling Techniques

An electromagnetic (EM) model is not the same as an electromagnetic compatibility (EMC) model. Nonetheless, accounting for the 3D electromagnetic interactions that determine the coupling from or to cables and equipment within their housing (ie. a geometrically complicated vehicle body-shell) is an essential element of the wider analysis that is needed in order to predict functional EMC effects. A single monolithic simulation for such purposes is not a practicable proposition, so a combination of appropriate modelling techniques represents the most viable approach to developing a functional EMC model [7]. For building an EMC model, we can consider a range of modelling techniques operating at a number of different levels [8] as outlined in Table 1 below. However, the most computationally expensive elements of such models (in time and computing resources) are the full 3D electromagnetic field ("class A") computations. Thus, there may also be advantages in hybridizing different "class A" models in order to maximize the efficiency of the 3D field calculation, particularly for electrically large systems such as vehicles at high frequencies [9].

Model class	Model order	Model nature	Objectives
A	3D + time or frequency	Electromagnetic - volume or surface meshing	3D electromagnetic field distribution and related parameters (eg. antenna characteristics)
B	2D static	Electrostatic - planar or peripheral meshing	Lumped circuit models of transmission line segments (valid for small spacing)
C	1D + time or frequency	Transmission line - linear meshing	Accounting for wave propagation effects on transmission lines (length and load dependent)
D	0D + time or frequency	Circuit simulation – lumped element behavioural models	Device behaviour in circuit models, but no account of physical layout

Table 1: Classification of model types required to predict functional EMC performance

A number of well-established numerical techniques can be applied to electromagnetic field modelling problems [10], examples of which include:

- boundary elements (BEM), also known as the method of moments (MoM) – unstructured surface mesh usually operating in frequency domain;
- finite elements (FEM) – unstructured volume mesh usually in frequency domain;
- finite volumes in time domain (FVTD) – unstructured volume mesh;
- finite differences in time domain (FDTD) – structured volume mesh;
- transmission line matrix (TLM) – structured volume mesh usually in time domain.

It can be seen that these methods are normally formulated in the time or frequency domain, using either structured or unstructured meshes. The relative merits of these approaches are summarized in Table 2, showing that no single technique is ideally suited to all types of problems. Selection of a suitable technique is therefore a compromise based on the capability, limitations and computing requirements of the numerical method in the proposed application.

Operation	Advantages	Disadvantages
Time domain	Good description of transients and non-linear problems. Entire frequency spectrum from a single simulation. Calculation time depends on the size of the mesh.	Difficult to account for frequency dependence of materials (cables, absorbers, soils etc.). Accommodating multiple-domain approaches (signal processing requirements). Calculation time for resonant structures.
Frequency domain	Accounting for frequency dependent materials. Analysis of restricted frequency ranges.	Calculations made at single frequencies. Frequency step required to generate a sufficiently detailed frequency response.
Unstructured mesh	Piece-wise linear approximation for curved surfaces.	Computing requirements increase rapidly with number and complexity of surfaces. Reals required to describe element locations.
Structured mesh	Computing requirements independent of number and complexity of surfaces. Integer description of cell locations.	"Staircased" approximation of curved surfaces using hexahedral cells.

Table 2: Relative merits of different types of electromagnetic simulation

3. Practical Vehicle Modelling Issues

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 representation of a 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. However, even when suitable CAD data, modelling tools and computing resources are available, many practical difficulties remain in the development of computational electromagnetics (CEM) models for complex systems such as vehicles [11].

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.

The first problem to be resolved in pre-processing is to acquire geometrical data for the 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.

After the geometrical data has been collated it is necessary to define a meshing strategy that meets the constraints of the selected numerical technique and the requirements of the analysis application, and then impose this scheme on the geometrical model in order to obtain the discretized CEM model. 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) during import and/or export;
- 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 CEM 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 manufacturers the opportunity to extract the maximum value possible from their existing investments in CAD processing and mesh generation activities.

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 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.

The volume of data that can result from such calculations is such that information overload is a potential problem that should not be underestimated in the post-processing phase. Thus, the time that is required to process the results of the simulations into a form that can be absorbed and interpreted by the analyst, and subsequently explained to non-specialists in this field, can also become a very significant proportion of the overall effort.

4. Vehicle Development Applications

One of the early targets for electromagnetic simulation is to support the robust packaging of electronic modules and sensors in addition to analysing the effects of potential harness routings. Modern vehicles utilise highly complex body structures and the electromagnetic fields vary significantly around the vehicle. The position of relatively sensitive electronic components such as non-contact position sensors or radio receivers may therefore be optimised to exploit the natural distribution effects of the surrounding geometry. This may ultimately allow EMC specifications to be relaxed for some modules, or perhaps even enable module performance margins to be "traded" within the system to ensure that vehicle level requirements can be achieved at minimal cost.

Harness routings are normally defined solely by the mechanical criteria of the harness size, flexibility and the available package space. Simulation will drive a new set of harness routing guidelines that will encompass not only the mechanical limitations but also the coupling effects, which the harness may experience. In some cases, it may not be possible to find alternative locations for parts predicted to be in EM hot spots. In these cases, additional steps such as higher levels of component immunity tests or preventative measures such as shielded cables or enclosures may be utilised.

A further area where whole vehicle electromagnetic modelling can be used to assist vehicle development is in antenna engineering. The structure of the vehicle can have a profound impact on the installed performance of vehicle antennas, and numerical modelling can be used to investigate these issues [12-13].

After-market radio transmitters and hand-held mobile phones can pose significant risk of electromagnetic interference in modern vehicles. In particular, hand-held mobile transmitters, which may be placed very close to vehicle electronics, could couple more energy into a victim system than fields emanating from outside the vehicle. Furthermore, the European Automotive EMC directive (95/54/EC [1]) is currently under review, and when the latest draft is adopted, vehicle manufacturers will be obliged to publish information relating to suitability of on-board transmitters including frequency bands, transmit power levels and antenna positions. However, it is very difficult, if not impossible, for a vehicle manufacturer to test for all possible combinations of equipment, frequencies, installation permutations and possible places where a user may fit an antenna. Simulations could be used to evaluate the severity of field strengths generated by many antenna positions with a view to test a small subset representing the worst case. An example of simulating on board transmitters is shown in figure 1 below with an antenna placed in the centre of the roof. If the simulation results were verified during the worst-case tests, then the manufacturer would be able to allow much more flexibility for the custom installations of after market radio transmitters.

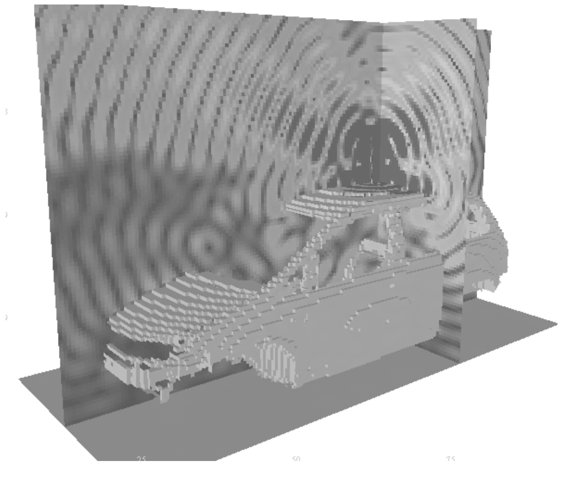

Figure 1: Simulation of an on-board transmitter to evaluate fields inside the vehicle

5. EMC Testing Applications

Current practices for vehicle level radiated immunity testing involve exposing vehicles to external interference from multiple directions, roaming phones (mobile phones) in targeted places and exterior antennas located at 'typical' installation positions. This approach, combined with stringent tests at subsystem level, has been efficient in designing vehicles that are robust to external interference. However, increasing vehicle complexity, numbers of modules and, more importantly, vehicle shapes and variants mean that it is not economical to repeat traditional tests as listed above in all possible vehicle permutations.

Simulations can be conducted to gain a better understanding of test coverage achieved by numerous physical tests. Results from this type of simulation are shown in figures 2-4, comparing the field strength profile inside a vehicle when exposed to an external field, an onboard transmitter with external antenna and a hand held mobile phone. It can be seen that some parts of the vehicle are not exposed to the intended field strength while some parts, which are in hot spots. This increased understanding of field coverage can be used for determining which additional positions to test with mobile phones or where to install an on board antenna for actual tests.

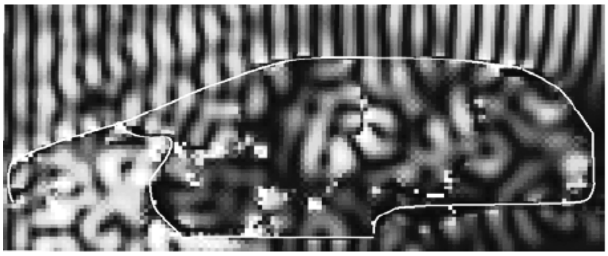

Figure 2: Simulation of internal fields due to an external source

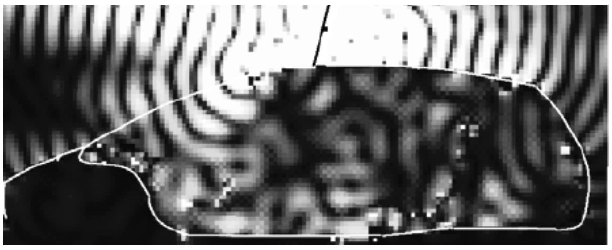

Figure 3: Internal fields generated by an exterior transmitter located on the roof

Figure 4: Fields generated by a transmitter located between two front seats

Conducting EMC simulations to identify worst-case fields around the vehicle will help the development team to better direct tests. For example, it could be possible to use simulation data to compare test severity levels generated from different exposure directions for off-board immunity. It would be possible to establish if testing from a particular direction actually generates more stringent fields compared to the 'standard' exposure angle. Tests can than be optimised for the worst-case.

Another area where simulations will help is in the selection of a subset of vehicles for test: current procedures for this are merely based on engine type, transmission, body shape and vehicle trim level (base, sports, luxury etc.). The use of numerical modelling to quantify the electromagnetic impact of optional vehicle features has already been demonstrated [14].

A further exploitation of simulation tools is envisaged in the area of component test methods for radiated immunity and radiated emissions. Vehicle manufacturers rely heavily on their suppliers to design and validate modules that are robust to external interference and do not produce excessive emissions. These parameters are communicated in EMC engineering specifications and verified through standard test procedures defined by international committees such as CISPR, SAE and ISO. On close inspection, it can be seen that each test procedure attempts to provide a physical simulation of the vehicle environment. In some cases, these test methods do not replicate vehicle environment very well, mainly due to fixed harness lengths and the presence of the uniform ground plane specified in standards. As a result of this discrepancy, there are occasional cases where issues detected during a vehicle level test cannot be replicated in component level tests, and vice versa. Field strength data obtained by simulating component level radiated immunity test setups can be compared to vehicle simulations to establish compatibility of field strengths around the proposed locations for modules. This information can enable vehicle manufacturers to better specify test severity levels for modules, thus avoiding over or under testing.

Simulation tools can also be used very efficiently to increase the understanding of component level tests. Simulations of component level tests are relatively easy compared to vehicles as these involve fixed geometries, such as a predefined size ground plane, 1m above the ground, with few antenna types. This increased understanding is now being used when making decisions to rectify problems observed during component tests, such as "failures" that may occur at the resonance frequency of the test fixture. There is an opportunity to improve some of the key test procedures used in the industry through simulations

6. Conclusions

Although automotive electromagnetic modelling is still an emerging technology, it is already being used in support of vehicle EMC engineering in a number of ways. In particular, vehicle level simulations can be used to:

- optimise the placement of electronic modules, harness routes and antennas;
- develop more realistic sub-system specifications;
- identify additional tests to be executed in order to ensure even coverage of all electronic systems;
- eliminate tests that result in less severe conditions compared to other tests (e.g. if the combination of off-board and hand-held mobile phone test produces higher field intensity in all of the vehicle compared to an antenna located in the middle of the roof, this test can be eliminated);
- reduce on-board transmitter tests to few locations that will produce the worst-case fields inside the vehicle cabin, whilst providing a detailed installation guide based on simulation data.

In the future, however, whole vehicle electromagnetic modelling will provide the basis for more comprehensive chains of models that aim to predict functional EMC performance.

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