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NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO TECHNICAL REPORT 59

Electromagnetic Compatibility in the Defense Systems of Future Years

(La compatibilité électromagnétique des systèmes de défense de l’avenir)

Report of the RTO Sensors and Electronics Technology Panel (SET) Working Group WG-01.

Published June 2002

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by the following 7 bodies:

AVT	Applied Vehicle Technology Panel
HFM	Human Factors and Medicine Panel
IST	Information Systems Technology Panel
NMSG	NATO Modelling and Simulation Group
SAS	Studies, Analysis and Simulation Panel
SCI	Systems Concepts and Integration Panel
SET	Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Electromagnetic Compatibility in the Defense Systems of Future Years

(RTO TR-059 / SET-005)

Executive Summary

The recent increasing recognition of EMC problems is based on two facts (detailed below), calling for an activity of assessment of the state of the art and a forecast of future trends.

The first fact is the increasing number of electronic equipment in every system, and the miniaturization of the devices that can be achieved by the new technologies. The consequence is the requirement for higher and higher frequencies and the increased likelihood of interference. The impact on the design at system level is evident: better tools are needed to estimate the system performance and to specify the EMC constraints, considering that conventional rules of thumb are inadequate to describe systems which are electromagnetically complex.

The second fact of concern about EMC in the military environment is related to the coexistence and harmonization between commercial and military standards. In fact, military standards are mainly concerned with the immunity of equipment and their operation in the same installation (e.g., aircraft, fixed station, etc.), with less concern for the ‘external world’. Commercial standards, on the contrary, seek a ‘pacific’ coexistence of all equipment (i.e., reduced emissions and sufficient immunity).

Airborne platforms are foreseen to increase the number of on-board transmitters for satellite and ground communications, self defense, monitoring and surveillance systems. The introduction of new technologies, relying largely on miniaturization and high speed, is triggered by the reduced weight of the equipment and the increased bandwidth of information processing.

Procurement Agencies may experience difficulties specifying the EMC requirements of next generation systems, because new technologies involve physical phenomena and frequency ranges of little concern in the past. The ability to produce correct specifications must rely on the updated knowledge of the state of the art in technology, and has a great economical impact, since reduce the risk for over/under specified systems which prove to be costlier.

The study has focussed on three areas of EMC design, development and qualification in future defence systems. The limitations of existing techniques and standards have been examined and highlighted. Such limitations cause risks at the present time. However, the risks will increase as a result of changes in the commercial and technological environment. Potential increases in risk, as a result of these changes in the absence of research development, have been highlighted. Furthermore, recommendations on investment in research and development have been made in order to mitigate the increasing risks.

La compatibilité électromagnétique des systèmes de défense de l’avenir

(RTO TR-059 / SET-005)

Synthèse

La reconnaissance croissante actuelle des problèmes de CEM a pour origine deux états de fait (explicités ci-dessous) qui appellent une activité de définition de l’état actuel des connaissances dans ce domaine, ainsi que la prévision des tendances futures.

Le premier fait constaté est le nombre croissant de composants électroniques intégrés dans chaque système, ainsi que la miniaturisation des dispositifs désormais permise par les nouvelles technologies. Il en résulte une demande de fréquences de plus en plus hautes, associée à la probabilité accrue d’interférences. L’impact sur la conception au niveau systèmes est évident : de meilleurs outils sont demandés pour évaluer les performances des systèmes et pour spécifier les contraintes CEM, étant donné que les règles empiriques traditionnelles ne suffisent plus à décrire des systèmes électromagnétiques complexes.

Le deuxième élément de préoccupation dans le domaine de la CEM militaire concerne le degré de coexistence et d’harmonisation entre les normes militaires et les normes commerciales. En effet, les normes militaires portent principalement sur l’immunité des équipements et leur fonctionnement au sein d’une même installation (par exemple, aéronef, station fixe etc..), et concernent moins le “monde extérieur”. Les normes du commerce, visent au contraire la coexistence “pacifique” de l’ensemble des équipements (c’est-à-dire la réduction des émissions et une immunité suffisante).

Le nombre d’émetteurs aéroportés destinés aux communications terrestres et par satellite, à l’autodéfense, et aux systèmes de contrôle et de surveillance doit normalement augmenter. La mise en application de ces nouvelles technologies, qui privilégient la miniaturisation et la vitesse, s’explique par la masse réduite des équipements et par l’augmentation de la bande passante utilisée pour le traitement de l’information.

Les agences d’achat pourraient rencontrer des difficultés lors de la spécification des besoins CEM de la prochaine génération de systèmes, parce que les nouvelles technologies entraînent des bandes passantes et des phénomènes physiques peu connus jusqu’ici. La capacité d’établir des spécifications correctes passe par des connaissances actualisées des technologies de pointe, et produit un impact économique considérable, car elle permet de réduire le risque de fabrication de systèmes inadéquats et par conséquent, plus coûteux.

L’étude a privilégié les trois aspects de la conception, du développement et de la qualification des futurs systèmes de défense. Les limites des techniques et des normes existantes ont été examinées et mises en évidence. Aujourd’hui, de telles limites ont pour effet de créer des risques. Mais de tels risques seront plus nombreux à l’avenir en raison de l’évolution de l’environnement commercial et technologique. Les risques possibles, qui résulteraient de ces changements, en l’absence d’activités de recherche, ont été soulignés. En outre, des recommandations ont été faites concernant l’investissement en recherche et développement qui serait à faire afin d’atténuer les effets de ces risques accrus.

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The Working Group WG01

- ***Approved***

  1997 by Agard SPP Panel

- ***Membership***

- BELGIUM:
  J. Catrysse
- CANADA:
  J. Seregelyi
- FRANCE:
  C. Alliot
- GERMANY:
  D. Jaeger, J. Nitsch
- ITALY:
  B. Audone, F. Canavero
- the NETHERLANDS:
  H. Clemens
- UK:
  N. Carter, I. MacDiarmid
- USA:
  M. Kanda

- ***Coordination meetings***

- 23/24 Apr. 1998: kickoff meeting (Turin, IT)
- 14 Sept. 1998: 2nd meeting (Rome, IT)
- 16 Feb. 1999: 3rd meeting (Zurich, CH)
- 25/26 Oct. 1999: 4th meeting (Turin, IT)

1. INTRODUCTION AND MOTIVATION

Background

The recent increasing recognition of EMC problems is based on two facts (detailed below), calling for an activity of assessment of the state of the art and a forecast of future trends.

The first fact is the increasing number of electronic equipment in every system, and the miniaturization of the devices that can be achieved by the new technologies. The consequence is the requirement for higher and higher frequencies and the increased likelihood of interference. The impact on the design at system level is evident: better tools are needed to estimate the system performance and to specify the EMC constraints, considering that conventional rules of thumb are inadequate to describe systems which are electromagnetically complex.

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Military Benefit

Airborne platforms are foreseen to increase the number of on-board transmitters for satellite and ground communications, self defense, monitoring and surveillance systems. The introduction of new technologies, relying largely on miniaturization and high speed, is triggered by the reduced weight of the equipment and the increased bandwidth of information processing.

Procurement Agencies may experience difficulties specifying the EMC requirements of next generation systems, because new technologies involve physical phenomena and frequency ranges of little concern in the past. The ability to produce correct specifications must rely on the updated knowledge of the state of the art in technology, and has a great economical impact, since reduce the risk for over/under specified systems which prove to be costlier.

Objectives

The objective of this RSG is twofold.

<u>State of the art of prediction techniques in EMC</u>

The activity of the RSG will aim at the assessment of the state of the art of the techniques (both analytical and numerical) that can be used for the prediction of system performance. Open problems which require further investigation will also be identified.

<u>Commercial vs. military EMC standards: future perspectives</u>

The aim of the RSG is to provide an understanding on how military equipment can operate in a world ruled by commercial specifications, and possibly how (and if) commercial standards (which are less expensive for the industry to fulfill) can be adopted by military organizations.

Summary

The study has focussed on three areas of EMC design, development and qualification in future defence systems, namely:

Numerical modelling
Test techniques
Published standards

The limitations of existing techniques and standards have been examined and highlighted. Such limitations cause risks at the present time. However, the risks will increase as a result of changes in the commercial and technological environment and potential increases in risk as a result of these changes in the absence of research development, have been highlighted. Furthermore, recommendations on investment in research and development have been made in order to mitigate the increasing risks.

2. EXAMINATION OF THE LIMITATIONS OF MODELLING AND TESTING

2.1 Description of Generic Processes.

The nature of design, development and qualification in EMC results in a process which is a well balanced combination of designing within guidelines, modelling and testing at component, equipment and complete system level. At the present time the balance between testing and modelling is determined by the limitations of modelling the phenomena. This balance could be shifted with considerable business benefits if modelling capabilities could be enhanced.

A generic EMC design, development and qualification process that applies to any system is shown in Fig.1. The diagram shows a progression of stages of maturity of a project down the middle. The EMC activities are shown in bold shadowed boxes on either side with arrows showing contributions to the various stages of maturity. The final basis for qualification consists of data of five different forms, namely:

- Whole system test data
- Component & equipment test data
- Documented design guidance data
- Documented concessions against the guidance
- Modelling results

It can be seen that there is a balance of test and modelling activities in the process.

The Role of Modelling.

It can be seen that modelling contributes to the process at all stages. It is used to explore design options at the conceptual design phase, provide the basis for equipment procurement specifications and engineering design guides. Later in the programme detailed design options and conflicts are explored using modelling.

Finally, modelling supports the component, equipment and whole system test programmes. Such input includes support for the design of test rigs, determination of the details of the procedure, exploration of areas that cannot be tested (once validated) and provision of corrections to remove the effects of the test conditions.

The Role of Testing.

The role of testing at the present time is larger than is desirable as a result of the lack of capability available in modelling. If the modelling had a wider bandwidth capability it could be used for all examination of the linear transfer functions and testing could be limited to validating the modelling and exploration of the system behaviours involving non-linearity and active component upset behaviour. However, due to present limitations testing must also be used to explore the higher frequency transfer functions above 100MHz.

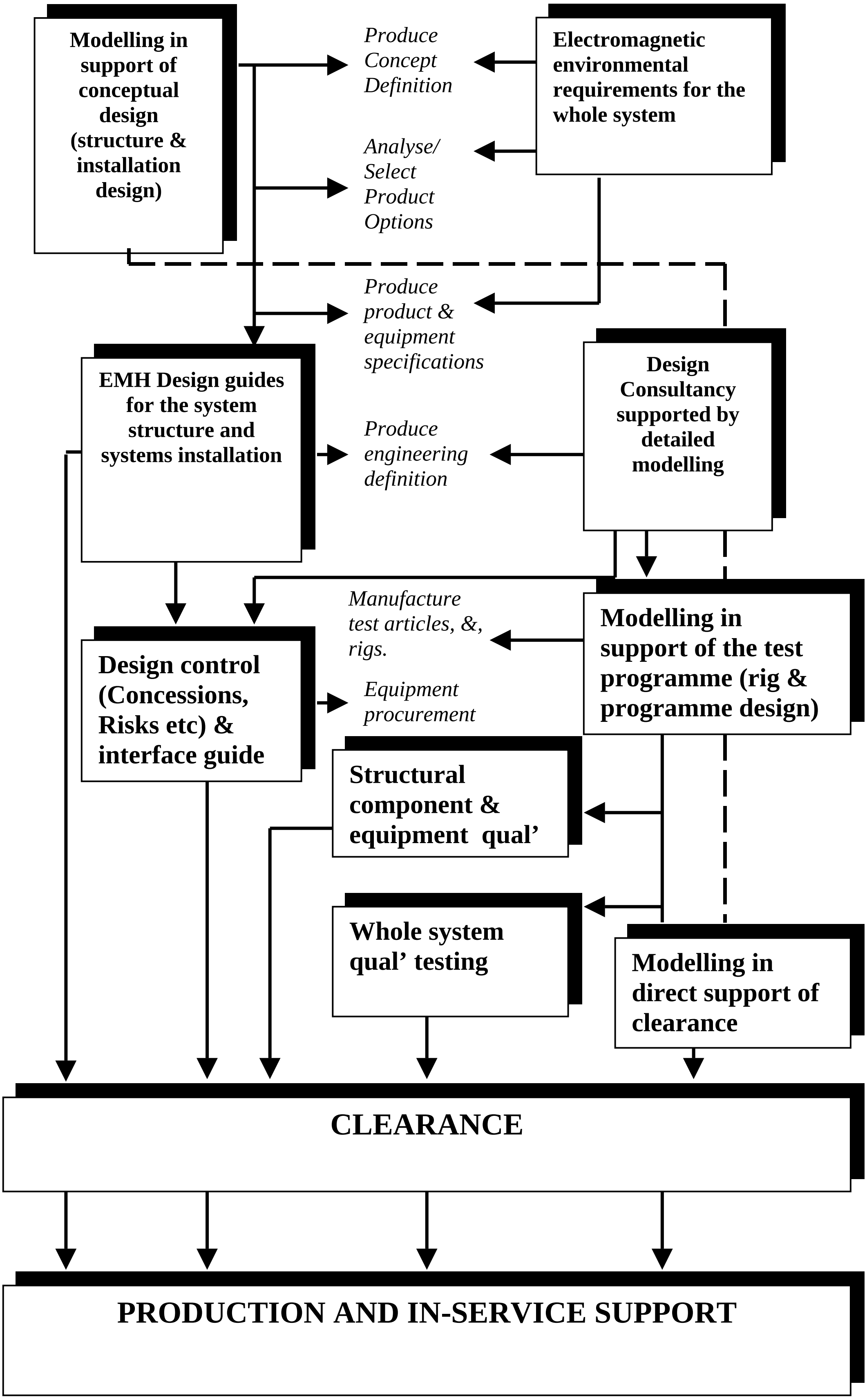


Fig.1 The Electromagnetic Hazard Protection Design and Clearance Process Framework

2.2 Numerical modelling and present limitations.

Computer techniques have revolutionized the way in which electromagnetic problems are analyzed. Antenna and microwave engineers rely heavily on computer methods to analyze and help evaluate new designs or design modifications. Although most EM problems ultimately involve solving only one or two partial differential equations subject to boundary constraints, very few practical problems can be solved without the aid of a computer.

Computer methods for analyzing problems in electromagnetics generally fall into one of three categories, analytical techniques, numerical techniques, and expert systems. Analytical techniques make simplifying assumptions about the geometry of a problem in order to apply a closed-form solution. Numerical techniques attempt to solve fundamental field equations directly, subject to the boundary constraints posed by the geometry. Expert systems do not actually calculate the field directly, but instead estimate values for the parameters of interest based on a rules database.

A number of computer programs based on analytical techniques are available to the EMC engineer. Some are very simple and run on personal computers. Others are very elaborate and run on supercalculators. Analytical techniques can be a useful tool when the important EM interactions of the configuration can be anticipated. However, most EMC problems of interest are simply too unpredictable to be modeled using this approach.

Expert systems approach a problem in much the same way as a quick-thinking, experienced EM engineer with a calculator would approach it. As system design and board layout procedures become more automated, expert system EM software will certainly play an important rôle. Neverthless, expert systems are no better than their rules database and it is unlikely that they will ever be used to model or understand, for example, the complex EM interactions that cause EMI sources to radiate.

Numerical techniques generally require more computation than anlytical techniques or expert systems, but they are very powerful EM analysis tools. Without making a priori assumptions about which field interactions are most significant, numerical techniques analyze the entire geometry provided as input. They calculate the solution to a problem based on a *full-wave* analysis.

A number of different numerical techniques for solving electromagnetic problems are available. Each numerical technique is well-suited for the analysis of a particular type of problem. The numerical technique used by a particular EM analysis program plays a significant role in determining what kinds of problems the program will be able to analyze.

This report reviews and summarize the main numerical electromagnetic modeling techniques that can be used for analyzing electromagnetic configurations. Several references are cited to aid the reader who wishes to investigate a particular technique in more detail.

Modeling choices in computational electromagnetics

Classification of electromagnetic problems

Problem classification is an important concept because the general theory and methods of solution usually apply only to a given class of problems. Classifying EM problems will help engineers to answer the question of what method is best for solving a given problem. Continuum problems are categorized differently depending on the particular item of interest, which could be one of these :

- The solution region,
- The nature of the equation describing the problem,
- The associated boundary conditions.

It is evident that these classifications are sometimes not independent of each other.

Classification of solution regions

In terms of the solution region or problem domain, the problem could be an interior problem, also variably called an inner, closed, or bounded problem, or an exterior problem, also variably called an outer, open, or unbounded problem.

Consider the solution region R with boundary S, as shown in figure 2.1. If part or all of S is at infinity, R is exterior/open, otherwise R is interior/closed. For example, wave propagation in a waveguide is an interior problem, whereas while wave propagation in free space, scattering of EM waves by raindrops, and radiation from a dipole antenna are exterior.

A problem can also be classified in terms of the electrical, constitutive properties *(σ, ε, μ)* of the solution region. This solution region could be linear (or nonlinear), homogeneous (or inhomogeneous), and isotropic (or anisotropic).

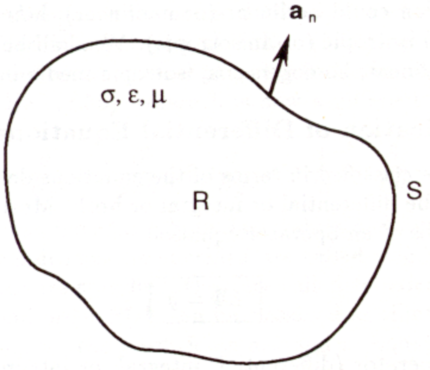


Figure 2.1: Solution region R with boundary S.

Classification of differential equations

EM problems are classified in terms of the equations describing them. The equations could be differential or integral or both. Most EM problems can be stated in terms of an operator equation :

$$L\Phi = g \qquad (2\text{-}1)$$

where *L* is an operator (differential, integral, or integro-differential), *g* is the known excitation or source, and *Φ* is the unknown function to be determined.

EM problems involve linear, second-order differential equations. In general, a second-order partial differential equation (PDE) is given by :

$$a\frac{\partial^2\Phi}{\partial x^2} + b\frac{\partial^2\Phi}{\partial x\partial y} + c\frac{\partial^2\Phi}{\partial y^2} + d\frac{\partial\Phi}{\partial x} + e\frac{\partial\Phi}{\partial y} + f\Phi = g \qquad (2\text{-}2)$$

The coefficients *a*, *b*, and *c* in general are functions of coordinates *x* and *y* ; they may also depend on *Φ* itself, in which case the PDE is said to be *nonlinear*. Since most EM problems involve linear PDE, *a*, *b*, and *c* will be regarded as constants. A PDE in which *g(x,y)* in equation (2-2) equals zero is termed *homogeneous* ; it is *inhomogeneous* if *g(x,y)* ≠ 0. Notice that equation (2-2) has the same form as equation (2-1), where *L* is now a differential operator given by :

$$L = a\frac{\partial^2}{\partial x^2} + b\frac{\partial^2}{\partial x\partial y} + c\frac{\partial^2}{\partial y^2} + d\frac{\partial}{\partial x} + e\frac{\partial}{\partial y} + f \; = g \qquad (2\text{-}3)$$

A PDE in general can have both boundary values and initial values. PDEs whose boundary conditions are specified are called *steady-state equations*. If only initial values are specified, they are called *transient equations*.

Any linear second-order PDE can be classified as elliptic, hyperbolic, or parabolic depending on the coefficients *a*, *b*, and *c*. Equation (2-2) is said to be :

Elliptic if $b^2 - 4ac < 0$
Hyperbolic if $b^2 - 4ac > 0$ (2-4)
Parabolic if $b^2 - 4ac = 0$

The terms *hyperbolic*, *parabolic*, and *elliptic* are derived from the fact that the quadratic equation :

$$ax^2 + bxy + cy^2 + dx + ey + f = 0 \qquad (2\text{-}5)$$

represents a hyperbola, parabola, or ellipse if $b^2 - 4ac$ is positive, zero, or negative, respectively.

Elliptic PDEs are associated with steady-state phenomena, i.e., boundary-value problems. Typical examples of this type of PDE include Laplace’s equation and Poisson's equation. An elliptic PDE usually models an interior problem, and hence the solution region is usually closed or bounded.

Hyperbolic PDEs arise in propagation problems. The solution region is usually open so that a solution advances outward indefinitely from initial conditions while always satisfying specified boundary conditions.

Parabolic PDEs are generally associated with problems in which the quantity of interest varies slowly in comparison with the random motions which produce the variations. The most common parabolic PDE is the diffusion equation in one dimension. Like hyperbolic PDE, the solution region for parabolic PDE is usually open. The initial and boundary conditions typically associated with parabolic equations resemble those for hyperbolic problems except that only one initial condition at $t = 0$ is necessary since the equation is only first order in time. Also, parabolic and hyperbolic equations are solved using similar techniques, whereas elliptic equations are usually more difficult and require different techniques.

The type of problem represented by equation (2-1) is said to be *deterministic*, since the quantity of interest can be determined directly. Another type of problem where the quantity is found indirectly is called *nondeterministic* or *eigenvalue*. The standard *eigenproblem* is of the form :

$$L\Phi = \lambda\Phi \qquad (2\text{-}6)$$

where the source term in equation (2-1) has been replaced by $\lambda\Phi$. A more general version is the *generalized eigenproblem* having the form :

$$L\Phi = \lambda M\Phi \qquad (2\text{-}7)$$

where M, like L, is a linear operator for EM problems. In equations (2-6) and (2-7), only some particular values of λ called *eigenvalues* are permissible ; associated with these values are the corresponding solutions Φ called *eigenfunctions*. Eigenproblems are usually encountered in vibration and waveguide problems where the eigenvalues λ correspond to physical quantities such as resonance and cutoff frequencies, respectively.

Classification of boundary conditions

The problem consists of finding the unknown function Φ of a partial differential equation. In addition to the fact that Φ satifies (2-1) within a prescribed solution region R, Φ must satisfy certain conditions on S, the boundary of R. Usually these boundary conditions are of the Dirichlet and Neumann types. Where a boundary has both, a mixed boundary condition is said to exist.

- Dirichlet boundary condition :

$$\Phi(r) = 0, \quad \text{r on S} \qquad (2\text{-}8)$$

- Neumann boundary condition:

$$\frac{\partial\Phi(r)}{\partial n} = 0, \quad \text{r on S} \qquad (2\text{-}9)$$

i.e., the normal derivative of Φ vanishes on S.

- Mixed boundary conditions :

$$\frac{\partial\Phi(r)}{\partial n}+h(r)\Phi(r)=0, \quad \text{r on S} \qquad (2\text{-}10)$$

where $h(r)$ is a known function and $\frac{\partial\Phi(r)}{\partial n}$ is the directional derivative of Φ along the outward normal to the boundary S, i.e. :

$$\frac{\partial\Phi}{\partial n}=\nabla\Phi\bullet a_n \qquad (2\text{-}11)$$

where a_n is a unit normal directed out of R. Note that the Neumann boundary condition is a special case of the mixed condition with $h(r) = 0$. The conditions in equations (2-8) to (2-10) are called *homogeneous boundary conditions*. The more general ones are the inhomogeneous :

Dirichlet :

$$\Phi(r)=p(r), \quad \text{r on S} \qquad (2\text{-}12)$$

Neumann :

$$\frac{\partial\Phi(r)}{\partial n}=q(r), \quad \text{r on S} \qquad (2\text{-}13)$$

Mixed :

$$\frac{\partial\Phi(r)}{\partial n}+h(r)\Phi(r)=w(r), \quad \text{r on S} \qquad (2\text{-}14)$$

where $p(r)$, $q(r)$, and $w(r)$ are explicitly known functions on the boundary S. For example, $\Phi(0) = 1$ is an inhomogeneous Dirichlet boundary condition, and the associated homogeneous counterpart is $\Phi(0) = 0$. Also $\Phi'(1) = 2$ and $\Phi'(1) = 0$ are, respectively, inhomogeneous and homogeneous Neumann boundary conditions. In electrostatics, for example, if the value of electric potential is specified on S, we have Dirichlet boundary condition, whereas if the surface charge ($\rho_s = D_n = \varepsilon\frac{\partial V}{\partial n}$) is specified, the boundary condition is Neumann. The problem of finding a function Φ that is harmonic in a region is called Dirichlet problem (or Neumann problem) if Φ (or $\frac{\partial\Phi}{\partial n}$) is prescribed on the boundary of the region.

It is worth observing that the term « homogeneous » has been used to mean different things. The solution region could be homogeneous meaning that σ, ε, and μ are constant within R ; the PDE could be homogeneous if $g = 0$ so that $L\Phi = 0$; and the boundary conditions are homogeneous when $p(r) = q(r) = w(r) = 0$.

Alternative modeling approaches available for CEM

There are four major, first principles, models in computational electromagnetics, given by:

Frequency Domain Integral Equation (FDIE) models remain the most widely studied and used models; they were the first to receive detailed development.

Frequency Domain Differential Equation (FDDE) models, whose use has also increased considerably in recent years, although most work to date has emphasized low-frequency applications.

Time Domain Differential Equation (TDDE) models, the use of which has increased tremendously over the past several years, primiraly as a result of much and faster computers.

Time Domain Integral Equation (TDIE) models, although available for more than 30 years, have gained increased attention in the past decade. The recent advances in this area make these methods very attractive for a large variety of applications.

It is worth mentioning several of the advantages in performing time domain modeling. First, wide band data are made available from one model computation as opposed to the frequency domain approach, in which many frequency samples are required to obtain the equivalent data. Second, it provides a more straightforward approach in modeling impedance nonlinearities in the time domain. Third, time domain models can handle time variations of load impedances.

Besides physical interpretability, there are two basic reasons for modeling in the time domain which provide a distinct advantage in most applications in which transient results are available:

- The first reason is the computational efficiency: For certain problems and/or approaches, fewer arithmetic operations are required when performed in the time domain. For example, in applications in which the early time peak response of an object to an impulsive field is sought, a time domain model offers an intrinsically more efficient approach compared to a frequency domain model, which requires frequency samples across a broad bandwidth followed by a Fourier (or other) transform to obtain the desired result. When seeking broadband information, a time domain model is also a more natural choice because it provides a transient response whose bandwidth is limited only by the frequency content of the excitation and the time and space sampling used in developing the model. In addition, time domain models may offer a naturally better match to massively parallel computer architectures than do frequency domain models.
- The second reason is the problem requirement: Problems that involve nonlinear or components can usually be modeled in a more straightforward and efficient manner in time domain, as can problems involving time-varying media and components. An additional benefit of time domain modeling is that time gating can be used in modeling, as in measurements, to remove the effects of unwanted reflections or to simulate larger objects. An example of the latter application is that of replacing an infinite cylindrical antenna model with a three-dimensional (3D) wire model whose behavior at a midpoint feed at early times, prior to end reflections, will be identical to that of an infinite structure [2-1]. Finally, body resonances, or singularity expansion method (SEM) poles, may be computed more directly from a time domain model.

Evolution of Time Domain Modeling

Representative examples of the growing variety of time domain research include the original TDDE approach by Yee [2-2] which forms the basis of the widely used finite-difference time domain (FDTD) model. An extensive survey of the application of this method is available [2-3]. A related application of a TDIE to acoustics was presented by Mitzner [2-4]. This work was closely followed by TDIE EM applications [2-5 to 2-8]. An alternative implementation of TDDE models was shortly thereafter initiated as the transmission-line method (TLM) by Johns and Beurle [2-9]. Recently, TD versions of the method of lines (TDML) and the geometrical theory of diffraction (TDGTD) were presented by Nam et al. [2-10] and Veruttipong [2-11], respectively. It seems likely that TD versions of other modeling approaches can also be expected to be developed.

Accompanying this initial research into TD CEM models was continuing work of a more analytical nature, including a series of papers in the early 1960s, one of which was a study by Brundell [2-12] on transient current waves propagating azimuthally around an infinite circular cylinder. Related papers by Wu [2-13] and Einarsson [2-14] investigated the impulse response of an infinite dipole antenna. Another fundamental analytical study of antennas excited by impulsive sources was presented by Franceschetti and Papas [2-15], Tijhuis et al. [2-16] reexamined a classical problem, the transient response of a thin, straight wire.

An increasing amount of TDIE modeling has followed. For example, Miller et al. [2-17] emphasized wire applications of the electric field IE (EFIE) which is further developed together with surface modeling using the magnetic field IE (MFIE) [2-18]. Other examples of developing TD models include Lui and Mei [2-19], Bennett [2-20 to 2-21], Bennett and Mieras [2-22 to 2-23], Gomez et al. [2-24], Marx [2-25], Bretones et al. [2-26], Gomez et al. [2-27 to 2-28], Rao and Wilton [2-29], Vechinski et al. [2-30 to 2-31] and Walker et al. [2-32 to 2-33]. Application examples have grown commensurately, as demonstrated by some nonlinear modeling [2-34 to 2-35], and as illustrated by using the time-gating feature of TD modeling for simulating infinite structures with a 3D wire model [2-1]. Selective overviews of this early TD research are given by Bennett and Ross [2-36], Miller and Landt [2-37], and Miller [2-38 to 2-39].

Althrough the literature devoted to time domain EM is rapidly expanding, there are few books devoted to the topic. Three edited books are by Felsen [2-40], Rao [2-41] and Miller [2-42]. The two former cover a variety of topics in time domain modeling and analysis, whereas the later systematically addresses the topic of time domain measurements in Electromagnetics together with an associated discussion of modeling and signal processing applications. Also, books by Kunz and Lubbers [2-43] and Taflove [2-44] are devoted exclusively to the FDTD formulation, whereas the TLM is the topic of a book by Christopoulos [2-45]. Recent edited books devoted to a related topic, ultra-wideband EM, include Noël [2-46], Bertoni et al. [2-47], and Taylor [2-48], whereas Lamensdorf and Susman [2-49] presented work on pulsed antennas.

Finite Element Methods

The finite element method (FEM) has its origin in the field of structural analysis. Although the earlier mathematical treatment of the method was provided by Courant [3-1] in 1943, the method was not applied to electromagnetic (EM) problems until 1968. Since then the method has been employed in diverses areas such as waveguide problems, electric machines, semiconductor devices, microstrips, and absorption of EM radiation by biological bodies. For a review of the historical development of FEM, the interested reader is referred to textbooks that are exclusively devoted to the FEM.

Although the finite difference method (FDM) and the method of moments (MOM) are conceptually simpler and easier to program than the finite element method (FEM), FEM is a more powerful and versatile numerical technique for handling problems involving complex geometries and inhomogeneous media. The systematic generality of the method makes it possible to construct general-purpose programs for solving a wide range of problems. Consequently, programs developed for a particular discipline have been applied successfully to solve problems in a different field with little or no modification [3-2].

Electrical engineers use finite element methods to solve complex, nonlinear problems in magnetics and electrostatics. Until recently however, very little practical modeling of 3-dimensional electromagnetic radiation problems was performed using this technique. There were two reasons for this. First, practical three-dimensional vector problems require significantly more computation than two-dimensional or scalar problems. Second, spurious solutions known as *vector parasites* often result in unpredictable, erroneous results. However, recent developments in this field [3-3, 3-4] appear to have solved the vector parasite problem. An increasing availability of computer ressources coupled with a desire to model more complex electromagnetic problems has resulted in a wave of renewed interest in finite element methods to solve EM radiation problems.

The first step in finite-element analysis is to divide the configuration into a number of small homogeneous pieces or *elements*. An example of a finite-element model is shown in figure 3-1. The model contains information about the device geometry, material constants, excitations and boundary constraints. The elements can be small where geometric details exist and much larger elsewhere. In each finite element, a simple (often linear) variation of the field quantity is assumed. The corners of the elements are called *nodes*.

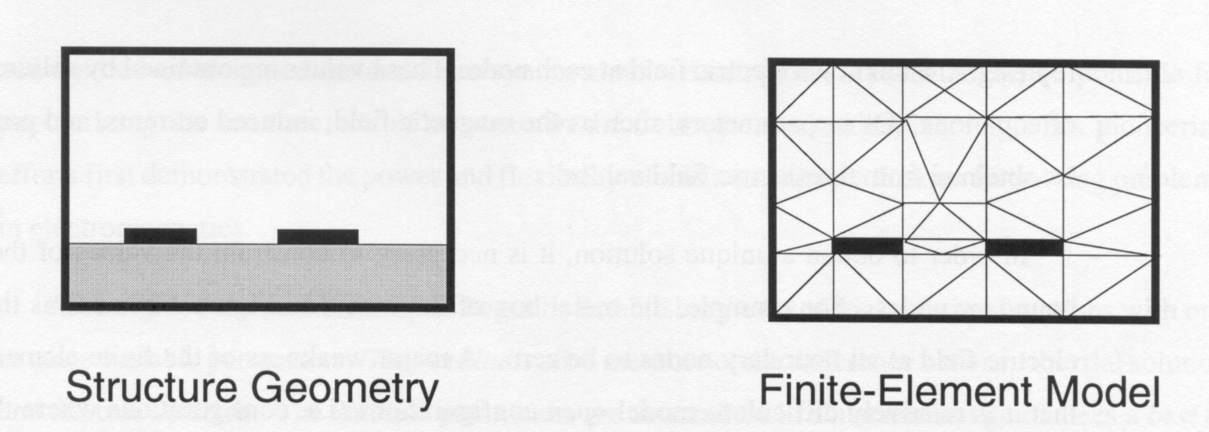


Figure 3.1: Finite-Element Modeling Example.

The finite element analysis of any problem involves basically four steps [3-5]:

- Discretizing the solution region into finite number of *subregions* or *elements*,
- Deriving governing equations for a typical element,
- Assembling of all elements in the solution region, and
- Solving the system of equations obtained.

Most finite element methods are variational techniques. Variational methods work by minimizing or maximizing an expression that is known to be stationary about the true solution. Generally, finite-element analysis techniques solve for the unknown field quantities by minimizing an energy functional. The energy functional is an expression describing all the energy associated with the configuration being analyzed. For 3-dimensional, time-harmonic problems this functional may be represented as:

$$F = \int_{\upsilon} \frac{\mu|\mathbf{H}|^2}{2} + \frac{\varepsilon|\mathbf{E}|^2}{2} - \frac{\mathbf{J}\cdot\mathbf{E}}{2j\omega} dv \qquad (3\text{-}1)$$

The first two terms in the integrand represent the energy stored in the magnetic and electric fields and the third term is the energy dissipated (or supplied) by conduction currents.

Expressing H in terms of E and setting the derivative of this functional with respect to E equal to zero, an equation of the form *f(J,E) = 0* is obtained. A k^{th}-order approximation of the function *f* is then applied at each of the *N* nodes and boundary conditions are enforced, resulting in the system of equations:

$$\begin{bmatrix} \mathbf{J}_1 \\ \mathbf{J}_2 \\ . \\ . \\ \mathbf{J}_n \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & . & . \\ y_{21} & y_{22} & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & y_{nn} \end{bmatrix} \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \\ \\ \\ \mathbf{E}_n \end{bmatrix} \qquad (3\text{-}2)$$

The values of J on the left-hand side of this equation are referred to as the source terms. They represent the known excitations. The elements of the *Y*-matrix are functions of the problem geometry and boundary constraints. Since each element only interacts with elements in its own neighborhood, the *Y*-matrix is generally sparse. The terms of the vector on the right-hand side represent the unknown electric field at each node. These values are obtained by solving the system of equations. Other parameters, such as the magnetic field, induced currents, and power loss can be obtained from the electric field values.

In order to obtain a unique solution, it is necessary to constrain the values of the field at all boundary nodes. For example, the metal box of the model in figure 3-1 constrains the tangential electric field at all boundary nodes to be zero. A major weakness of the finite element method is that it is relatively difficult to model *open* configurations (i.e. configurations where the fields are not known at every point on a closed boundary). Various techniques such as *ballooning* and *absorbing boundaries* are used in practice to overcome this defiency. These techniques work reasonably well for 2-dimensional problems, but so far they are not very effective for 3-dimensional electromagnetic radiation problems.

The major advantage that finite element methods have over other EM modeling techniques stems from the fact that the electrical and geometric properties of each element can be defined independently. This permits the problem to be set up with a large number of small elements in regions of complex geometry and fewer, larger elements in relatively open regions. Thus it is possible to model configurations that have complicated geometries and many arbitrarily shaped dielectric regions in a relatively efficient manner.

Commercial finite element codes [3-6, 3-7] are available that have graphical user interfaces and can determine the optimum placement of node points for a given geometry automatically. These codes are used to model a wide variety of electromagnetic devices such as spark plugs, transformers, waveguides, and integrated circuits.

Specific implementations of three-dimensional electromagnetic finite element codes are described in Ph.D. dissertations by Maile [3-8] and Webb [3-9]. Silvester and Ferrari [3-10] have written an excellent text on this subject for electrical engineers.

One of the major difficulties encountered in the finite element analysis of continuum problems is the tedious and time-consuming effort required in data preparation. Discretization of the continuum involves dividing up the solution region into subdomains, called *finite elements*. Figure 3-2 shows some typical elements for one-, two-, and three-dimensional problems. Efficient finite element programs must have node and element generating schemes, referred to collectively as *mesh generators*. Automatic mesh generation minimizes the input data required to specify a problem. It not only reduces the time involved in data preparation, it eliminates human errors introduced when data preparation is performed manually. Combining the automatic mesh generation program with computer graphics is particularly valuable since the output can be monitored visually. As the solution regions become more complex than the ones considered previously, the task of developing mesh generators becomes more tedious. A number of mesh generation algorithms of varying degrees of automation have been proposed for arbitrary solution domains. Reviews of various mesh generation techniques can be found in [3-11, 3-12].

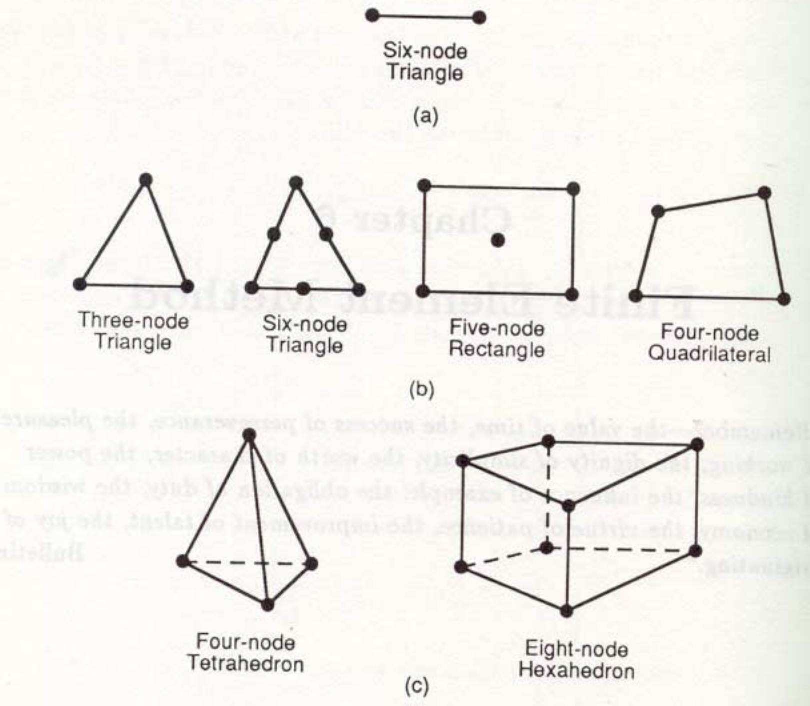


Figure 3-2: Typical finite elements:
a) One-dimensional,
b) Two-dimensional,
c) Three-dimensional.

The basic steps involved in a mesh generation are as follows [3-13]:

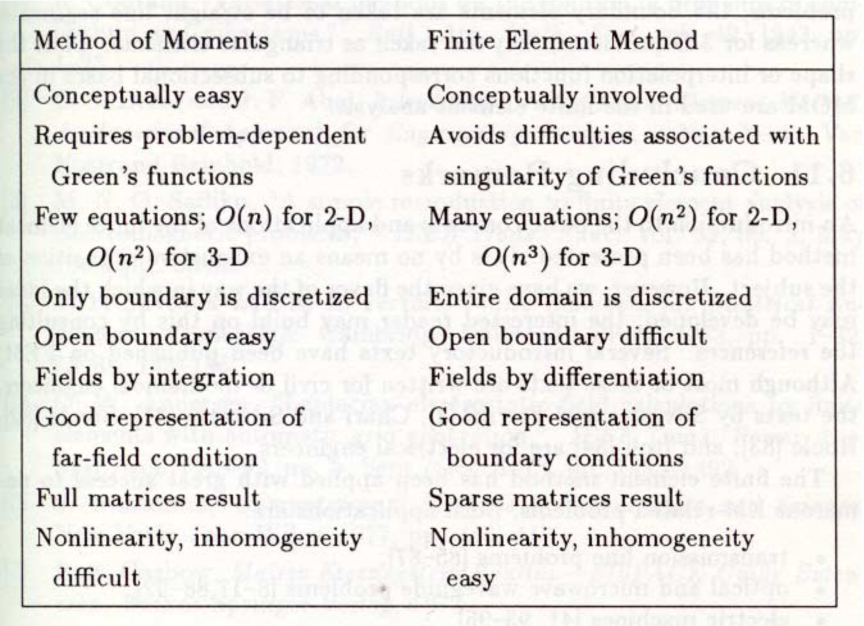
- Subdivide solution region into few quadrilateral blocks,
- Separately subdivide each block into elements,
- Connect individual blocks.

The accuracy of a finite element solution can be improved by using finer mesh or using higher order elements or both. A discussion on mesh refinement versus higher order elements is given by Desai and Abel [3-2]; a motivation for using higher order elements is given by Csendes in [3-14]. In general, fewer higher order elements are needed to achieve the same degree of accuracy in the final results. The higher order elements are particularly useful when the gradient of the field variable is expected to vary rapidly. They have been applied with great success in solving EM-related problems [3-10, 3-14 to 3-19].

Hybrid Finite Element Methods

To apply the FEM to exterior or unbounded problems such as open-type transmission lines (e.g., microstrip), scattering, and radiation problems poses certain difficulties. To overcome these difficulties, several approaches [3-20 to 3-30] have been proposed, all of which have strengths and weaknesses. Two common approaches are the infinite element method and the boundary element method.

The finite element method (FEM) and the method of moments (MOM) have become the two most popular methods of numerical analysis of electromagnetic problems. The choice between the two numerical techniques will usually depend on the particular problem, although both are ultimately capable of yielding the same information. The two methods result in a set of simultaneous equations. These equations look quite different from each other, and each set of equations presents its own peculiar problems. Perhaps the best way to compare MOM with FEM is shown in table 3.1. From the table, it is evident that the two methods have properties that complement each other. In view of this, hybrid methods have been proposed. These methods allow the use of both MOM and FEM with the aim of exploiting the strong points in each method.



Method of Moments	Finite Element Method
Conceptually easy	Conceptually involved
Requires problem-dependent Green's functions	Avoids difficulties associated with singularity of Green's functions
Few equations; $O(n)$ for 2-D, $O(n^2)$ for 3-D	Many equations; $O(n^2)$ for 2-D, $O(n^3)$ for 3-D
Only boundary is discretized	Entire domain is discretized
Open boundary easy	Open boundary difficult
Fields by integration	Fields by differentiation
Good representation of far-field condition	Good representation of boundary conditions
Full matrices result	Sparse matrices result
Nonlinearity, inhomogeneity difficult	Nonlinearity, inhomogeneity easy

Table: Comparison between Method of Moments and Finite Element Method [3-31]

One of these hybrid methods involves using the so-called boundary element method (BEM). It is a finite element approach for handling exterior problems [3-26 to 3-30]. It basically involves obtaining the boundary-integral equation from Green's identity and solving this by a discretization procedure similar to that used in regular finite element analysis. Since the BEM is based on the boundary integral equivalent to the governing differential equation, only the surface of the problem domain needs to be modeled. Thus the dimension of the problem is reduced by one as in MOM. For 2-D problems, the boundary elements are taken to be straight line segments, whereas for 3-D problems, they are taken as triangular elements. Thus the shape or interpolation functions corresponding to subsectional bases in the MOM are used in the finite element analysis.

Concluding remarks on FEM

The finite element method has been applied with great success to numerous EM-related problems. Such applications are :

- Transmission line problems,
- Optical and microwave waveguide problems,
- Electric machines,
- Semiconductor devices,
- Scattering problems,
- Human exposition to EM radiation,
- Others.

Moment Methods

Like finite-element analysis, the *method of moments* (or moment method) is a technique for solving complex integral equations by reducing them to a system of simpler linear equations. In contrast to the variational approach of the finite element method however, moment methods employ a technique known as the *method of weighted residuals*. Actually, the terms method-of-moments and method-of-weighted-residuals are synonymous. Harrington [4-1] was largely responsible for popularizing the term *method of moments* in the field of electrical engineering. His pioneering efforts first demonstrated the power and flexibility of this numerical technique for solving problems in electromagnetics.

All weighted residual techniques begin by establishing a set of trial solutions functions with one or more variable parameters. The *residuals* are a measure of the difference between the trial solution and the true solution. The variable parameters are determined in a manner that guarantees a *best fit* of the trial functions based on a minimization of the residuals.

The equation solved by moment method techniques is generally a form of the *electric field integral equation* (EFIE) or the *magnetic field integral equation* (MFIE). Both of these equations can be derived from Maxwell's equations by considering the problem of a field scattered by a perfect conductor (or a lossless dielectric). These equations are of the form:

$$\text{EFIE:} \quad \mathbf{E} = f_e(\mathbf{J}) \qquad (4\text{-}1)$$

$$\text{MFIE:} \quad \mathbf{H} = f_m(\mathbf{J}) \qquad (4\text{-}2)$$

where the terms on the left-hand side of these equations are incident field quantities and J is the induced current.

The form of the integral equation used determines which types of problems a moment-method technique is best suited to solve. For example one form of the EFIE may be particularly well suited for modeling thin-wire structures, while another form is better suited for analysing metal plates. Usually these equations are expressed in the frequency domain, however the method of moments can also be applied in the time domain.

The first step in the moment-method solution process is to expand J as a finite sum of basis (or expansion) functions:

$$\mathbf{J} = \sum_{i=1}^{M} J_i \mathbf{b_i} \qquad (4\text{-}3)$$

where b_i is the ith basis function and J_i is an unknown coefficient.

Next, a set of M linearly independent weighting (or testing) functions, w_j, are defined. An inner product of each weighting function is formed with both sides of the equation being solved. In the case of the MFIE (Equation 4-2), this results in a set of M independant equations of the form:

$$\langle w_j, \mathbf{H} \rangle = \langle w_j, f_m(\mathbf{J}) \rangle \qquad j = 1,2,....,M \qquad (4\text{-}4)$$

By expanding J using equation (4-3), we obtain a set of M equations in M unknowns:

$$\langle w_j, \mathbf{H} \rangle = \sum_{i=1}^{M} \langle w_j, f_m(J_i, \mathbf{b_i}) \rangle \qquad j = 1,2,....,M \qquad (4\text{-}5)$$

This can be written in matrix form as:

$$[\mathbf{H}] = [Z][\mathbf{J}] \qquad (4\text{-}6)$$

where:

$$Z_{ij} = \langle w_j, f_m(b_i) \rangle$$

$$\mathbf{J_i} = J_i$$

$$\mathbf{H_j} = \langle w_j, \mathbf{H_{inc}} \rangle$$

The vector H contains the known incident field quantities and the terms of the Z-matrix are functions of the geometry. The unknown coefficients of the induced current are the terms of the J vector. These values are obtained by solving the system of equations. Other parameters such as the scattered electric and magnetic fields can be calculated directly from the induced currents.

Depending on the form of the field integral equation used, moment methods can be applied to configurations of conductors only, homogeneous dielectrics only, or very specific conductor-dielectric geometries. Moment method techniques applied to integral equations are not very effective when applied to arbitrary configurations with complex geometries or inhomogeneous dielectrics. They also are not well-suited for analyzing the interior of conductive enclosures or thin plates with wire attachments on both sides [4-2].

Nevertheless, moment method techniques do an excellent job of analyzing a wide variety of important three-dimensional electromagnetic radiation problems. General purpose moment method codes are particurlarly efficient at modeling wire antennas or wires attached to large conductive surfaces. They are widely used for antenna and electromagnetic scattering analysis. Several non-commercial general-purpose moment-method computer programs are available [4-3, 4-4].

Concluding remarks on MOM

The method of moments is a powerful numerical method capable of applying weighted residual techniques to reduce an integral equation to a matrix equation. The solution of the matrix equation is usually carried out via inversion, elimination, or iterative techniques. Although MOM is commonly applied to open problems such as those involving radiation and scattering, it has been successfully applied to closed problems such as waveguides and cavities.

General concepts on MOM are covered in [4-5] and [4-6]. Clear and elementary discussions on the IEs and Green's functions may be found in [4-7 to 4-13]. For further study on the theory of the method of moments, one should see [4-1, 4-5, 4-8, 4-14, 4-15].

The number of problems that can be treated by MOM is endless. The following problems represent typical EM-related application areas:

- Electrostatic problems,
- Wire antennas and scatterers,
- Scattering and radiation from bodies of revolution,
- Scattering and radiation from bodies of arbitrary shape,
- Transmission lines,
- Aperture problems,
- Biomagnetic problems.

A number of user-oriented computer programs have evolved over the years to solve electromagnetic integral equations by the method of moments. These codes can handle radiation and scattering problems in both the frequency and time domains. Reviews of the code may be found in [4-16 to 4-18]. The most popular of these codes is the Numerical Electromagnetic Code (NEC) developed at the Lawrence Livermore National Laboratory [4-16, 4-19]. NEC is a frequency domain antenna modeling FORTRAN IV code applying the MOM to IEs for wire and surface structures. Its most notable features are probably that it is user oriented, includes documentation, and is available; for these reasons, it is being used in public and private institutions. A compact version of NEC is the mini-numerical electromagnetic code (MININEC) [4-20], which is intented to be used in personal computers.

It is important that we recognize the fact that MOM is limited in applications to radiation and scattering from bodies that are electrically large. The size of the scatterer or radiator must be of the order of λ^3. This is because the cost of storing, inverting, and computing matrix elements becomes prohibitively large. At high frequencies, asymptotic techniques such as the geometrical theory of diffraction (GTD) are usually employed to derive approximate but accurate solutions [4-21 to 4-23].

Finite Difference Time Domain Method

The Finite Difference Time Domain (FDTD) method is a direct solution of Maxwell's time dependent curl equations:

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \qquad (5\text{-}1)$$

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \qquad (5\text{-}2)$$

It uses simple central-difference approximations to evaluate the space and time derivatives [5-1 to 5-7].

The FDTD method is a time stepping procedure. Inputs are time-sampled analog signals. The region being modeled is represented by two interleaved grids of discrete points. One grid contains the points at which the magnetic field is evaluated. The second grid contains the points at which the electric field is evaluated.

A basic element of the FDTD space lattice is illustrated in figure 5-1. Note that each magnetic field vector component is surrounded by four electric field components. A first-order central-difference approximation can be expressed as:

$$\frac{1}{A}\left[E_{z1}(t)+E_{y2}(t)-E_{z3}(t)-E_{y4}(t)\right]=-\frac{\mu_0}{2\Delta t}\left[H_{x0.}(t+\Delta t)-H_{x0.}(t-\Delta t)\right] \quad \text{(5-3)}$$

where *A* is the area of the near face of the cell in figure 5-1. $H_{x0.}(t+\Delta t)$ is the only unknown in this equation, since all other quantities were found in a previous time step. In this way, the electric field values at time *t* are used to find the magnetic field values at time *t+Δt*. A similar central-difference approximation of equation (5-2) can then be applied to find the electric field values at time *t+2Δt* from the magnetic values at time *t+Δt*. By alternately calculating the electric and magnetic fields at each time step, fields are propagated throughout the grid.

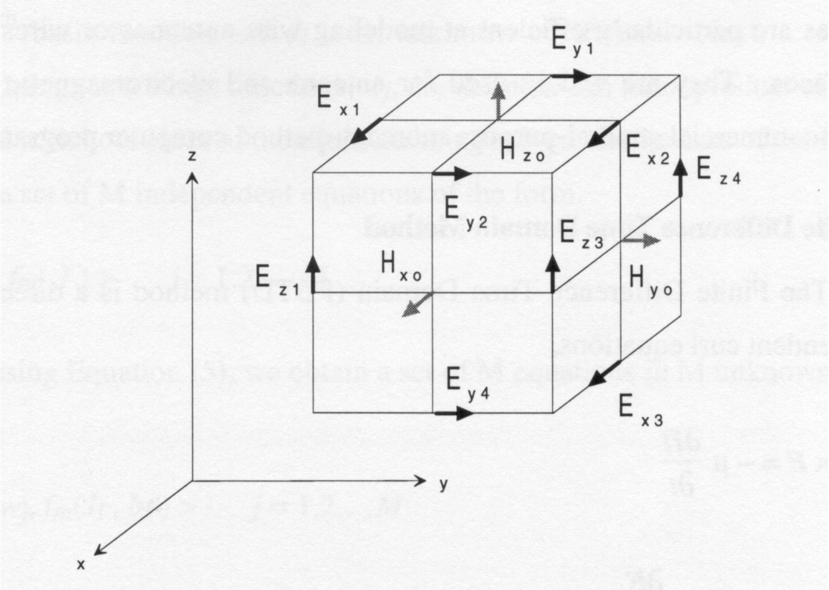


Figure 5-1: Basic Element of the FDTD Space Lattice.

Time stepping is continued until a steady state solution or the desired response is obtained. At each time step, the equations used to update the field components are fully explicit. No system of linear equations must be solved. The required computer storage and running time is proportional to the electrical size of the volume being modeled and the grid resolution.

Figure 5-2 illustrates an arbitrary scatterer embedded in a FDTD space lattice. Special absorbing elements are used at the outer boundary of the lattice in order to prevent unwanted reflexion of signals that reach this boundary [5-8 to 5-15]. Values of μ, ε and σ assigned to each field component in each cell define the position and electrical properties of the scatterer. These parameters can have different values for different field orientations permitting anisotropic materials to be modeled. Their values can also be adjusted at each time-step depending on conditions making it easy to model nonlinear materials.

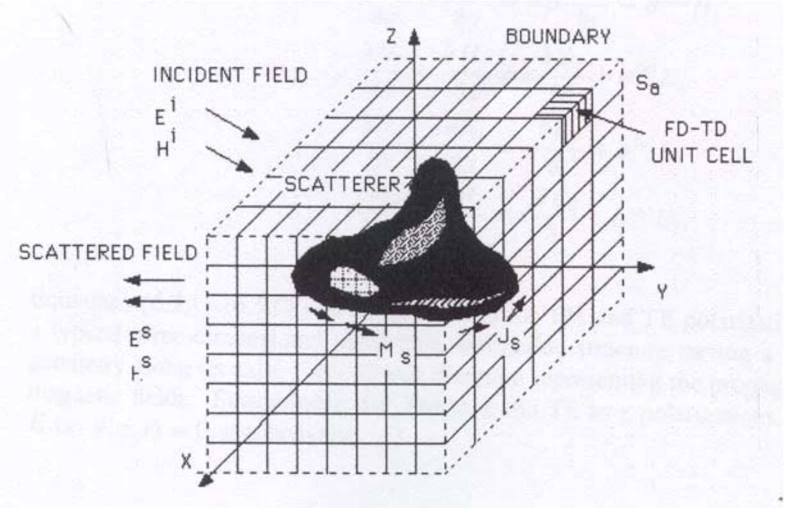


Figure 5-2 : Arbitrarily shaped three-dimensional material scatterer embedded in a FDTD structured space lattice.

Because the basic elements are cubes, curved surfaces on a scatterer must be staircased. For many configurations this does not present a problem. However for configurations with sharp, acute edges, an adequately staircased approximation may require a very small grid size. This can significantly increase the computational size of the problem. Surface conforming FDTD techniques with non-rectangular elements have been introduced to combat this problem. One of the more promising of these techniques, which permits each element in the grid to have an arbitrary shape, is referred to as the Finite-Volume Time-Domain (FVTD) method [5-16 to 5-29]. Figure 5-3 shows an example of meshing used for FVTD method.

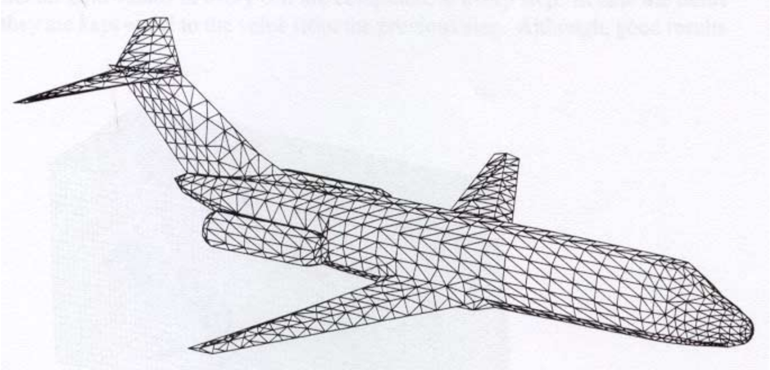


Figure 5-3: Meshing of an airplane.

Frequency domain results can be obtained by applying a discrete Fourier transform to the time domain results. This requires additional computation, but a wide-band frequency-domain analysis can be obtained by transforming the system's impulse response.

The FDTD and FVTD methods are widely used for radar cross section analysis although they have been applied to a wide range of EM modeling problems [5-30 to 5-40]. Their primary advantage is their great flexibility. Arbitrary signal waveforms can be modeled as they propagate through complex configurations of conductors, dielectrics, and lossy non-linear non-isotropic materials [5-41 to 5-47]. These techniques have also been developped in the frequency domain [5-48]. Another advantage of these techniques is that they are readily implemented on massively parallel computers, particularly vector processors and SIMD (single-instruction-multiple-data) machines.

The only significant disadvantage of this technique, is that the problem size can easily get out of hand for some configurations. The *fineness* of the grid is generally determined by the dimensions of the smallest features that need to be modeled. The volume of the grid must be great enough to encompass the entire object and most of the *near field*. Large objects with regions that contain small, complex geometries may require large, dense grids. When this is the case, other numerical techniques may be much more efficient than the FDTD or FVTD methods alone : a good approach is to combine the FVTD method with the standard FDTD method [5-49, 5-50]. Indeed, with the finite-volume method, we can use an unstructured conformal mesh to represent the object and its immediate neighborhood with relatively few cells. With the finite-difference method, we can use a structured mesh for the remaining part of the computational domain and apply an efficient boundary condition, for example, the PML formalism [5-9, 5-10] which reduces considerably the number of unknowns. The gain in CPU time can also be improved for both methods by using a local time step. For the finite-volume method, the stability condition on the time step leading to a convergent numerical scheme is :

$$dt \leq \min_i \left(\frac{1}{v} \frac{|V_i|}{\sum_{k=1}^{m_i} |S_k|} \right) \tag{5-4}$$

where $|V_i|$ is the volume of the cell V_i, m_i is the number of faces enclosing the cell V_i , S_k is the surface of the face k, and v is the speed of light in the medium. For the finite-difference scheme of Yee, this condition is given by :

$$dt \leq \min_i \left(\frac{1}{v} \frac{1}{\sqrt{\frac{1}{dx_i^2} + \frac{1}{dy_i^2} + \frac{1}{dz_i^2}}} \right) \tag{5-5}$$

where dx_i, dy_i, and dz_i are the lengths of the edges of a rectangular cell in the grid.

We observe that the stability criterion for the finite-volume method is generally more restrictive than that for the finite-difference method. This implies that if we can use the two different time steps for each numerical scheme, we can expect a reduction in CPU time.

Accuracy and stability of FD solutions

The question of accuracy and stability of numerical methods is extremely important if the solution is to be reliable and useful. Accuracy has to do with the closeness of the approximate solution to exact solutions (assuming they exist). Stability is the requirement that the scheme does not increase the magnitude of the solution with increase in time.

They are three sources of errors that are nearly unavoidable in numerical solution of physical problems:

- Modeling errors,
- Truncation (or discretization) errors,
- Roundoff errors.

Each of these error types will affect accuracy and therefore degrade the solution. The modeling errors are due to several assumptions made in arriving at the mathematical model. For example, a nonlinear system may be represented by a linear PDE. Truncation errors arise from the fact that in numerical analysis, we can deal only with a finite number of terms from processes which are usually described by infinite series. For example, in deriving finite difference schemes, some higher-order terms in the Taylor series expansion were neglected, thereby introducing truncation error. Truncation errors may be reduced by using finer meshes, that is, by reducing the mesh size and time increment. Alternatively, truncation errors may be reduced by using a large number of terms in the series expansion of derivatives, that is, by using higher-order approximations. However, care must be exercised in applying higher-order approximations. Instability may result if we apply a difference equation of an order higher than the PDE being examined. These higher-order difference equations may introduce "spurious solutions".

Roundoff errors reflect the fact that computations can be done only with a finite precision on a computer. This unavoidable source of errors is due to the limited size of registers in the arithmetic unit of the computer. Roundoff errors can be minimized by the use of double-precision arithmetic. The only way to avoid roundoff errors completely is to code all operations using integer arithmetic. This is hardly possible in most practical situations.

Although it has been noted that reducing the mesh size will increase accuracy, it is not possible to indefinitely reduce the mesh size. Decreasing the truncation error by using a finer mesh may result in increasing the roundoff error due to the increased number of arithmetic operations. A point is reached where the minimum total error occurs for any particular algorithm using any given word length [5-51]. This is illustrated in figure 5-4. The concern about accuracy leads us to question whether the finite difference solution can grow unbounded, a property termed the instability of the difference scheme. A numerical algorithm is said to be stable if a small error at any stage produces a smaller cumulative error. It is unstable otherwise. The consequence of instability (producing unbounded solution) is disastrous. To determine whether a finite difference scheme is stable, we define an error, ε^n, which occurs at time step n, assuming that there is one independent variable. We define the amplification of this error at time step $n+1$ as:

$$\varepsilon^{n+1} = g\varepsilon^{n} \qquad (5\text{-}6)$$

where g is known as the *amplification factor*.

The problems of stability and convergence of finite difference solutions are further discussed in [5-52, 5-53], while the error estimates in [5-54].

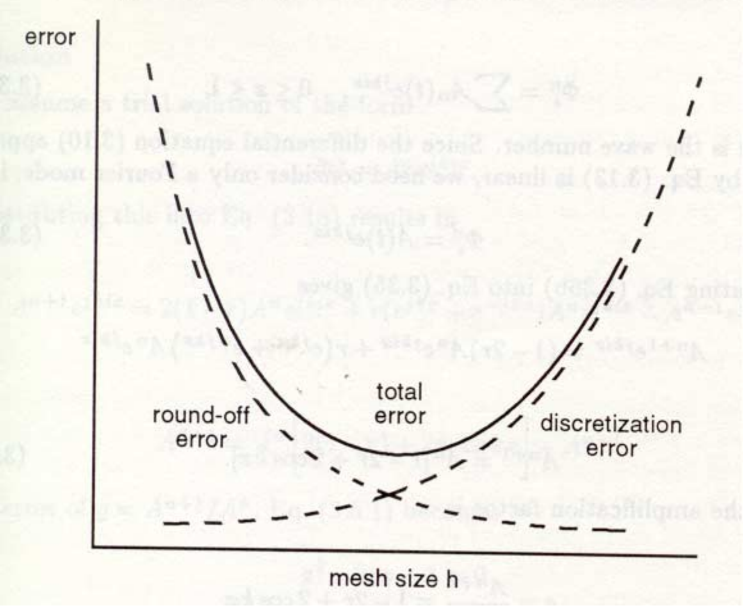


Figure 5-4: Error as a function of the mesh size.

Concluding remarks

As noted previously, the finite difference method has some inherent advantages and disadvantages. It is conceptually simple and easy to program. The finite difference approximation to a given PDE is by no means unique; more accurate expressions can be obtained by employing more elaborate and complicated formulas. However, the relatively simple approximations may be employed to yield solutions of any specified accuracy simply by reducing the mesh size provided that the criteria for stability and convergence are met.

A very important difficulty in finite differencing of PDEs, especially parabolic and hyperbolic types, is that if one value of the function Φ under study is not calculated and therefore set equal to zero by mistake, the solution may become unstable.

A serious limitation of the finite difference method is that interpolation of some kind must be used to determine solutions at points not on the grid.

Finite Difference Frequency Domain Method

Although conceptually the Finite Difference Frequency Domain (FDFD) method is similar to the Finite Difference Time Domain (FDTD) method, from a practical standpoint it is more closely related to the finite element method. Like FDTD, this technique results from a finite difference approximation of Maxwell's curl equations. However, in this case the time-harmonic versions of these equations are employed:

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H} \qquad (6\text{-}1)$$

$$\nabla \times \mathbf{H} = (\sigma + j\omega\varepsilon)\mathbf{E} \qquad (6\text{-}2)$$

Since there is no time stepping it is not necessary to keep the mesh spacing uniform. Therefore optimal FDFD meshes generally resemble optimal finite element meshes. Like the moment-method and finite-element techniques, the FDFD technique generates a system of linear equations. The corresponding matrix is sparse like that of the finite element method.

Although it is conceptually much simpler than the finite element method, very little attention has been devoted to this technique in the literature. Perhaps this is due to the *head start* that finite element techniques achieved in the field of structural mechanics.

There are apparently very few codes available that utilize this technique. A notable exception is the FDFD module that is included in the GEMACS software marketed by Advanced Electromagnetics [6-1].

Transmission Line Matrix Method

The link between field theory and circuit theory, the major theories on which electrical engineering is based, has been exploited in developing numerical techniques to solve certain types of partial differential equations arising in field problems with the aid of equivalent electrical networks. There are three ranges in the frequency spectrum for which numerical techniques for field problems in general have been developed. In terms of the wavelenght λ and the approximate dimension l of the apparatus, these ranges are:

- $\lambda >> l$
- $\lambda \ \# \ l$
- $\lambda << l$.

In the first range, the special analysis techniques are known as *circuit theory*, in the second, as *microwave theory*, and in the third, as *geometric optics* (frequency independent). Hence the fundamental laws of circuit can be obtained from Maxwell's equations by applying an approximation valid when $\lambda >> l$. However, it should be noted that circuit theory was not developed by approximating Maxwell's equations, but rather was developed independently from experimentally obtained laws. The connection between circuit theory and Maxwell's equations (summarizing field theory) is important; it adds to the comprehension of the fundamentals of electromagnetics. In fact, circuits are mathematical abstractions of physically real fields; nevertheless, electrical engineers at times feel they understand circuit theory more clearly than fields.

The idea of replacing a complicated electrical system by a simple equivalent circuit goes back to Kirchhoff and Helmholtz. As a result of Park's [7-1], Kron's [7-2, 7-3] and Schwinger's [7-4, 7-5] works, the power and flexibility of equivalent circuits become more obvious to engineers. The recent applications of this idea to scattering problems, originally due to Johns [7-6], has made the method more popular and attractive.

TLM basic concepts

The Transmission Line Matrix (TLM) method is similar to the FDTD method in terms of its capabilities, but its approach is unique. Like FDTD, analysis is performed in the time domain and the entire region of the analysis is gridded. Instead of interleaving E-field and H-field grids however, a single grid is established and the *nodes* of this grid are interconnected by virtual transmission lines. Excitations at the source nodes propagate to adjacent nodes through these transmission lines at each time step.

The symmetrical condensed node formulation introduced by Johns [7-7] has become the standard for three-dimensional TLM analysis. The basic structure of the symmetrical condensed node is illustrated in figure 7-1. Each node is connected to its neighboring nodes by a pair of orthogonally polarized transmission lines. Generally, dielectric loading is accomplished by loading nodes with reactive stubs. These stubs are usually half the length of the mesh spacing and have a characteristic impedance appropriate for the amount of loading desired. Lossy media can be modeled by introducing loss into the transmission line equations or by loading the nodes with lossy stubs. Absorbing boundaries are easily constructed in TLM meshes by terminating each boundary node transmission line with its characteristic impedance.

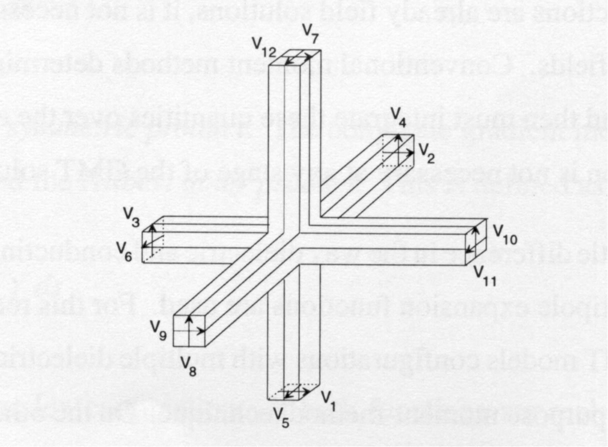


Figure 7-1: The Symmetrical Condensed Node.

Like other numerical techniques, the TLM method is a discretization process. Unlike other methods such as finite difference and finite element methods, which are mathematical discretization approaches, the TLM is a physical discretization approach. In the TLM, the discretization of a field involves replacing a continuous system by a network or array of lumped elements. For example, consider the one-dimensional system (a conducting wire) with no energy storage as in figure 7-2a. The wire can be replaced by a number of lumped resistors providing a discretized equivalent in figure 7-2b. The discretization of the two-dimensional, distributed field is shown in figure 7-3.

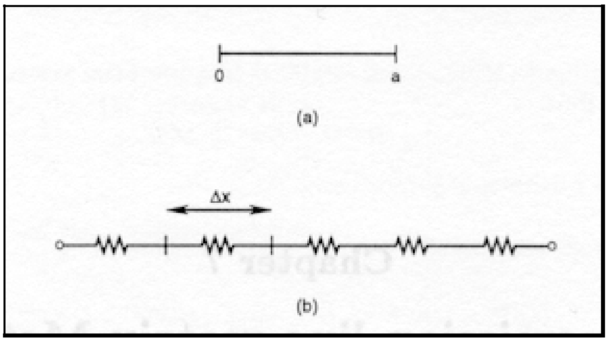


Figure 7-2: a) One-dimensional conducting system,
b) Discretized equivalent.

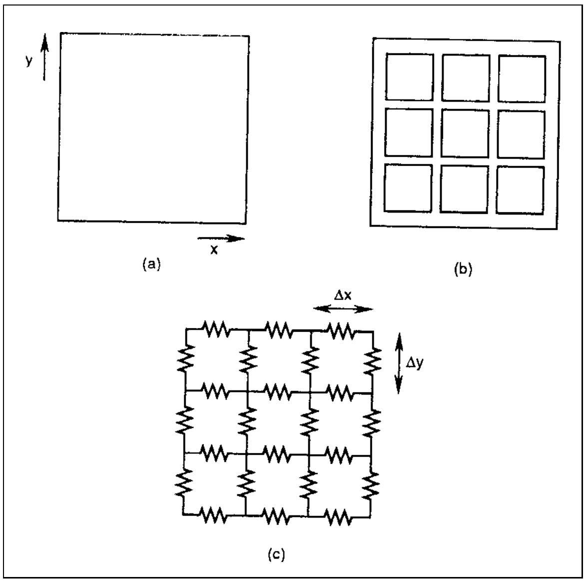


Figure 7-3 : a) Two-dimensional conductive sheet,
b) Partially discretized equivalent,
c) Fully discretized equivalent.

The TLM method involves dividing the solution region into a rectangular mesh of transmission lines. Junctions are formed where the lines cross forming impedance discontinuities. A comparison between the transmission-line equations and Maxwell's equations allows equivalence to be drawn between voltages and currents on the lines and electromagnetic fields in the solution region. Thus, the TLM method involves two basic steps:

- Replacing the field problem by the equivalent network and deriving analogy between the field and network quantities.
- Solving the equivalent network by iterative methods.

Figure 7-4 represents the dispersion curve of the velocity of waves in a two-dimensional TLM network. From this figure, we conclude that the TLM can represent Maxwell’s equations over the range of frequencies from zero to the first network cutoff frequency, which occurs at $\omega\Delta l/c = \pi/2$ or $\Delta l/\lambda = 1/4$. Over this range, the velocity of the waves behaves according to the characteristic of figure 7-4. For frequencies much smaller than the network cutoff frequency, the propagation velocity approximates to $1/\sqrt{2}$ of the free-space velocity.

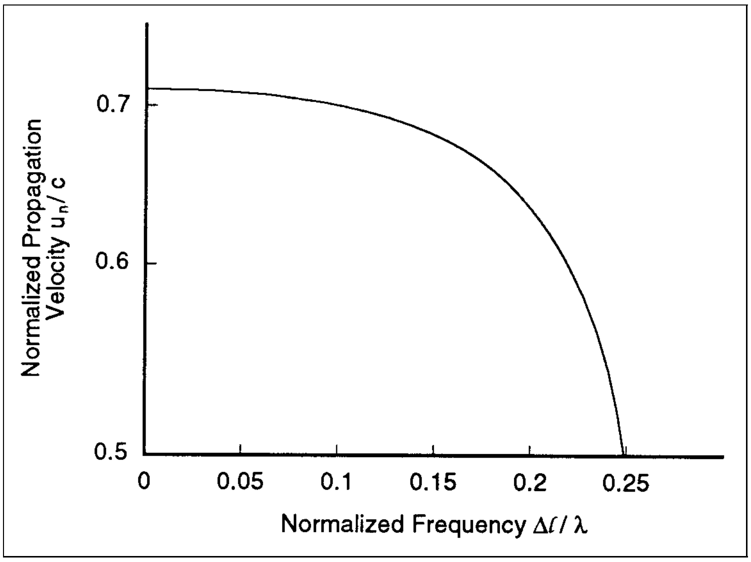


Figure 7-4 : Dispersion of the velocity of waves in a two-dimensional TLM network.

The dispersion relation for three-dimensional problems can be derived as :

$$\sin\left(\frac{\pi}{r}\cdot\frac{\Delta l}{\lambda}\right) = 2\sin\left(\pi\frac{\Delta l}{\lambda}\right) \qquad (7\text{-}1)$$

where r represents the normalized propagation velocity $(r = u_n/c)$.

Thus for low frequencies ($\Delta l/\lambda<0.1$), the network propagation velocity in three-dimensional space may be considered constant and equal to $c/2$.

Error sources and corrections

As in all approximate solutions such as the TLM technique, it is important that the error in the final result be minimal. In the TLM method, four principal sources of error can be identified:

- Truncation error,
- Coarseness error,
- Velocity error,
- Misalignment error.

Each of these sources of error and ways of minimizing it will be discussed in what follows.

Truncation error

The truncation error is due to the need to truncate the impulse response in time. As a result of the finite duration of the impulse response, its Fourier transform is not a line spectrum but rather a superposition of *sinx/x* functions, which may interfere with each other and cause a slight shift in their maxima.The maximum truncation error is given by :

$$e_T = \frac{\Delta S}{\Delta l / \lambda_c} = \frac{3\lambda_c}{SN^2\pi^2\Delta l} \qquad (7\text{-}2)$$

where λ_c is the cutoff wavelength to be calculated. ΔS is the absolute error in $\Delta l/\lambda_c$, S is the frequency separation (expressed in terms of $\Delta l/\lambda_c$, λ_c being the free-space wavelength) between two neighboring peaks as shown in figure 7-5, and N is the number of iterations. Equation (7-2) indicates that e_T decreases with increasing N and increasing S. It is therefore desirable to make N large and suppress all unwanted modes close to the desired mode by carefully selecting the input and output points in the TLM mesh. An alternative way of reducing the truncation error is to use a Hanning window in the Fourier transform [7-8, 7-9].

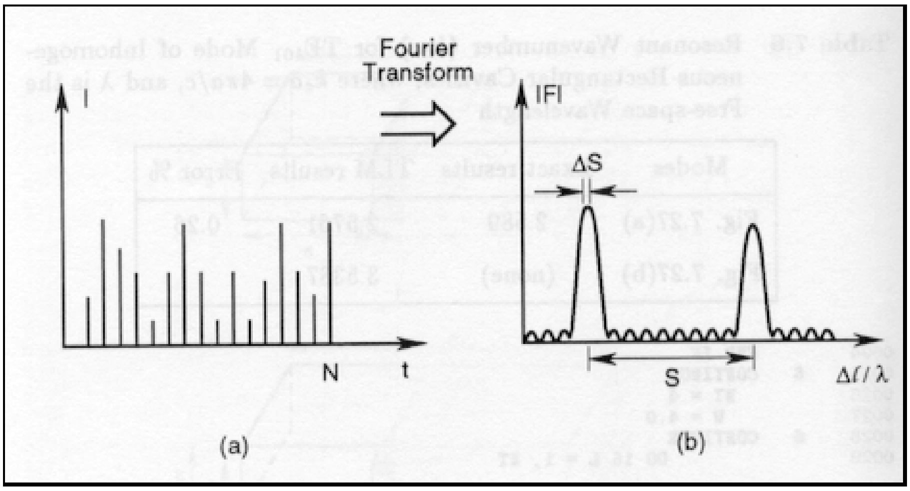


Figure 7-5 : Source of truncation error :
a) Truncated output impulse,
b) Resulting truncation error in the frequency domain.

Coarseness error

This occurs when the TLM mesh is too coarse to resolve highly nonuniform fields as can be found at corners and edges. An obvious solution is to use a finer mesh *($\Delta l \rightarrow 0$)*, but this would lead to large memory requirements and there are limits to this refinement. A better approach is to use variable mesh size so that a higher resolution can be obtained in the nonuniform field region [7-10]. This approach requires more complicated programming.

Velocity error

This stems from the assumption that propagation velocity in the TLM mesh is the same in all directions and equal to $u_n = u/\sqrt{2}$, where u is the propagation velocity in the medium filling the structure. The assumption is only valid if the wavelength λ_n in the TLM mesh is large compared with the mesh size Δl ($\Delta l/\lambda_n < 0.1$). Thus the cutoff frequency f_{cn} in the TLM mesh is related to the cutoff frequency f_c of the real structure according to $f_c = f_{cn}\sqrt{2}$. If Δl is comparable with λ_n, the velocity of propagation depends on the direction and the assumption of constant velocity results in a velocity error in f_c. Fortunately, a measure to reduce the coarseness error takes care of the velocity error as well.

Misalignment error

This error occurs in dielectric interfaces in three-dimensional inhomogeneous structures such as microstrip or fin line. Ait is due to the manner in which boundaries are simulated in a three-dimensional TLM mesh ; dielectric interfaces appear halfway between nodes, while electric and magnetic boundaries appear across such nodes. If the resulting error is not acceptable, one must make two computations, one with recessed and one with protruding dielectric, and take the average of the results.

Concluding remarks

Transmission-line modelling (TLM), otherwise known as the transmission-line-matrix method, is a numerical technique for solving field problems using circuit equivalent. It is based on the equivalence between Maxwell's equations and the equations for voltages and currents on a mesh of continuous two-wire transmission lines. The main feature of this method is the simplicity of formulation and programming for a wide range of applications [7-8]. As compared with the lumped network model, the transmission-line model is more general and performs better at high frequencies where the transmission and reflection properties of geometrical discontinuities cannot be regarded as lumped [7-4].

A comparison of the TLM method with the finite difference method can be interesting. While TLM provides a physical model, finite difference provides a mathematical model. According to Johns, the two methods complement each other rather than compete with each other [7-11].

The advantage of using the TLM method are similar to those of the FDTD method. Complex nonlinear materials are readily modeled. Impulse responses and the time-domain behavior of systems are determined explicitly. And, like FDTD, this technique is suitable for implementation on massively parallel machines. A major advantage of the TLM method , as compared with other numerical techniques, is the ease with which complicated structures can be analysed. The great flexibility and versatility of the method reside in the fact that the TLM mesh incorporates the properties of EM fields and their interaction with the boundaries and material media. Hence, the EM problem need not be formulated for every new structure. Thus a general-purpose program such as in [7-12] can be developed such that only the parameters of the structure need be entered for computation. Another advantage of using the TLM method is that certain stability properties can be deduced by inspection of the circuit. There are no problems with convergence, stability, or spurious solutions.

The disadvantage of the FDTD method are also shared by this technique. The primary disadvantage being that voluminous problems that must use a fine grid require excessive amounts of computation.

Nevertheless, both the TLM and FDTD techniques are very powerful and widely used. For many types of EM problems they represent the only practical methods of analysis. Deciding whether to utilize a TLM or FDTD technique is a largely personal decision. Many engineers find the transmission line analogies of the TLM method to be more intuitive and easier to work with. On the other hand, others prefer the FDTD method because of its simple, direct approach to the solution of Maxwell's field equations. The TLM method requires significantly more computer memory per node, but it generally does a better job of modeling complex boundary geometries. This is because both E and H are calculated at every boundary node.

A listing for a general purpose TLM code written in FORTRAN can be found in a Ph.D. dissertation by S. Akhtarzad [7-12]. This program can be adapted to a variety of applications. A general overview of the TLM method and a two-dimensional TLM code is provided in a book by Hoefer [7-13].

Generalized Multipole Technique

The Generalized Multipole Technique (GMT) is a relatively new method for analyzing EM problems. It is a frequency domain technique that (like the method of moments) is based on the method of weighted residuals. However, this method is unique in that the expansion functions are analytic solutions of the fields generated by sources located some distance away from the surface where the boundary condition is being enforced.

Moment methods generally employ expansion functions representing quantities such as charge or current that exist on a boundary surface. The expansion functions of the Generalized Multipole Technique are spherical wave field solutions corresponding to *multipole* sources. By locating these sources away from the boundary, the field solutions form a smooth set of expansion functions on the boundary and singularities on the boundary are avoided.

Like the method of moments, a system of linear equations is developed and then solved to determine the coefficients of the expansion functions that yield the best solution. Since the expansion functions are already field solutions, it is not necessary to do any further computation to determine the fields. Conventional moment methods determine the currents and/or charges on the surface first and then must integrate these quantities over the entire surface to determine the fields. This integration is not necessary at any stage of the GMT solution.

There is little difference in the way dielectric and conducting boundaries are treated by the GMT. The same multipole expansion functions are used. For this reason, a general purpose implementation of the GMT models configurations with multiple dielectrics and conductors much more readily than a general purpose moment-method technique. On the other hand, moment method techniques which employ expansion functions that are optimized for a particular type of configuration (e.g. thin wires), are generally much more efficient at modeling that specific type of problem.

Over the last ten years, the GMT has been applied to a variety of EM configurations including dielectric bodies [8-1, 8-2], obstacles in waveguides [8-3], and scattering from perfect conductors [8-4, 8-5]. Work in this young field is continuing and new developments are regularly announced. Recent significant developments include the addition of a thin-wire capability [8-6, 8-7] and a "ringpole" expansion function for modeling symmetric structures [8-8].

A commercial GMT code has been developed at the Swiss Federal Institute of Technology. This code is called the MMP (Multiple MultiPole) code. A two-dimensional PC version is available through Artech House Publishers [8-9]. A comprehensive text describing the GMT technique and the MMP code is also available [8-10].

Conjugate Gradient Method

The Conjugate Gradient Method is another technique based on the method of weighted residuals. It is very similar conceptually to conventional moment method techniques. Nevertheless, there are two features that generally distinguish this technique from other moment methods. The first has to do with the way in which the weighting functions are utilized. The second involves the method of solving the system of linear equations.

Conventional moment methods define the inner product of the weighting functions, w_j, with another function g as:

$$\langle w_j, g\rangle = \int_S \langle w_j \cdot g\rangle dS \qquad (9\text{-}1)$$

This is referred to as the *symmetric product*. The conjugate gradient method uses a different form of the inner product called the *Hilbert inner product*. This is defined as:

$$\langle w_j, g\rangle = \int_S \langle w_j \cdot g^*\rangle dS \qquad (9\text{-}2)$$

where the * denotes complex conjugation. If both functions are real, these two definitions are equivalent. However, when complex weighting functions are utilized, the symmetric product is a complex quantity and therefore not a valid *norm*. In this case, the Hilbert inner product is preferred [9-1].

The other major difference between conventional moment methods and the conjugate gradient method involves the technique used to solve the large system of equations these methods generate. Conventional moment method techniques generally employ a Gauss-Jordan method or another direct solution procedure. Direct solution techniques solve the system of equations with a given number of calculations (generally $O[N^3]$, where N is the order of the matrix).

Conjugate gradient methods utilize an iterative solution procedure. This procedure, called the *method of conjugate gradients*, can be applied to the system of equations or it can be applied directly to the operator equation [9-2]. Iterative solution procedures such as the method of conjugate gradients are most advantageous when applied to large, sparse matrices.

Boundary Element Method

The Boundary Element Method (BEM) is a weighted residual technique. It is essentially a moment-method technique whose expansion and weighting functions are defined only on a boundary surface. Most general purpose moment-method EM modeling codes employ a boundary element method [10-1, 10-4].

Like the finite element method, its origins are in the field of structural mechanics. Electrical engineers are likely to use the more general term *moment method* to describe an implementation of this technique. Outside of electrical engineering however, the terms *boundary element method* or *boundary integral element method* are commonly used.

High frequency methods

In many practical high frequency scattering problems, the scatterers are very large compared to wavelength. When high frequency radar cross section (RCS) is required, exact solution is impossible with current computer ressources. In this cases, approximate methods are very helpful. Typical approximate techniques are geometric optics (GO), physical optics (PO), geometric theory of diffraction (GTD), and physical theory of diffraction (PTD). These approximations have been incorporated into the shooting and bouncing ray (SBR) method [11-1].

Uniform Theory of Diffraction

The Uniform Theory of Diffraction (UTD) is an extension of the Geometrical Theory of Diffraction (GTD). Both of these techniques are high-frequency methods. They are only accurate when the dimensions of objects being analyzed are large relative to the wavelength of the field. In general, as the wavelengths of an electromagnetic excitation approach zero, the fields can be determined using geometic optics. UTD and GTD are extensions of geometric optics that include the effects of diffraction.

Diffraction is a local phenomena at high frequencies. Therefore, the behavior of the diffracted wave at edges, corners, and surfaces can be determined from an asymptotic form of the exact solution for simpler canonical problems. For example, the diffraction around a sharp edge is found by considering the asymptotic form of the solution for an infinite wedge. GTD and UTD methods add diffracted rays to geometric optical rays to obtain an improved estimate of the exact field solution.

The Basic Scattering Code (BSC) is a popular implementation of UTD. It is available from the ElectroScience Laboratory of the Ohio State University [11-2].

Fast far field approximation (FAFFA)

Another RCS estimation technique, called the fast far field approximation (FAFFA), has been developed [11-3]. The idea of this method is to compute the interactions between elements using different methods depending on the electrical distance between the elements. When the distance is small, exact interaction is calculated ; when the distance is large, a far field approximation is used. The field interactions are calculated iteratively using conjugate gradient (CG) method. The iteration process is equivalent to taking into account the higher order terms in GO, PO or PTD approximations. After several iterations, the results are found to be greatly improved over that of a simple PO or GO. On the other hand, this method can deal with small scale target geometry variations since it computes the near field interaction exactly hence it is more flexible to be applied to arbitrary complex targets. This algorithm has a computational complexity of $O(N^{1.33})$ and memory requirement of $O(N)$ for N unknown problems. The method differs from exact method since far field approximation is used. It also differs from pure PO since the solution is calculated iteratively so that the higher order scattering field, such as edge diffraction, surface wave and multiple-reflection, are automatically taken into account.

Hybrid Techniques

It is apparent from the previous sections that none of the techniques described is well-suited to all (or even most) electromagnetic modeling problems. Most moment method codes won't model inhomogeneous, nonlinear dielectrics. Finite element codes can't efficiently model large radiation problems. GMT and UTD codes are not appropriate for small, complex geometries or problems that require accurate determination of the surface and wire currents. Unfortunately, most practical printed circuit card radiation models have all of these features and therefore cannot be analyzed by any of these techniques.

One solution, which has been employed by a number of researchers, is to combine two or more techniques into a single code. Each technique is applied to the region of the problem for which it is best suited. The appropriate boundary conditions are enforced at the interfaces between these regions. Normally a surface integral technique such as the boundary element method will be combined with a finite method such as the finite element, FDTD, or TLM method. Several successful implementations of hybrid techniques are described in the literature [12-1, 12-10].

So far, none of the available hybrid techniques model the radiation from printed circuit cards very well. This is due to the fact that most of these methods were developed to predict radar cross section (RCS) values or for other scattering problems where the source is remote from the configuration being modeled. Work in this area is continuing however. Several researchers are involved in efforts to develop hybrid techniques that can be applied to a variety of presently intractable problems.

Advances in the development and implementation of codes based on a single technique continue to be important. However, there will always be problems that defy analysis by any one technique.
Hybrid methods permit numerical modeling techniques to be applied to a whole new class of configurations.

New numerical modelling techniques

Fast Multipole Method (FFM)

As shown in chapter 4, the EM field scattering by arbitrarily shaped conductor can be obtained by finding the solution of an integral equation where the unknown function is the induced current distribution. The integral equation is discretized into a matrix equation by the method of moments (MOM). The resultant matrix equation is then solved by Gaussian elimination, which requires O(N^3) floating-point operations if Gaussian elimination is used to solve *N* linear equations, or O(N^2) operations per iteration if the conjugate gradient (CG) method is used.
The fast multipole method (FMM) [13-1 to 13-6] speeds up the matrix-vector multiply in the conjugate gradient (CG) method when it is used to solve the matrix equation iteratively. FMM can be applied with the electric field integral equation (EFIE), the magnetic field integral equation (MFIE), and the combined field integral equation (CFIE). A FMM formula for CFIE has been derived, which reduces the complexity of a matrix-vector multiply from O(N^2) to O($N^{1.5}$), where *N* is the number of unknowns. With a nonnested method, using the ray-propagation fast multipole algorithm (RPFMA) [13-5, 13-6], the cost of a FMM matrix-vector multiply is reduced to O($N^{4/3}$). The authors of this technique have also implemented a multilevel fast multipole algorithm (MLFMA), whose complexity is further reduced to O(NlogN) [13-7]. To test the complexity, the electromagnetic scattering from a conducting sphere has been calculated using the combined-field integral equation (CFIE). The machine was the SGI Power Challenge with 4 processors (R8000) and 2 GB of memory. However, only one processor has been used for this simulation. The diameter of the sphere varied from 1.5 λ to 24 λ, the number of unknowns *(N)* ranged from 2352 to 602112, while the number of levels in MLFMA was from three to seven. The longest edge length was 0.15 λ, while the average edge length was 0.10 λ. The CPU time per iteration and the memory requirements are plotted as functions of the number of unknowns in figure 13-1. Two curves, $8\text{x}10^{-5}$NlogN and $2.7\text{x}10^{-3}$N, are also plotted in the same figure, for comparison. A total of 602112 unknowns, with a seven-level MLFMA, was used in the last point in figure 13-1. It consumed 12 hours on the Power Challenge using one processor {six hours were needed for setup (filling the matrix and calculating plane-wave expansion), four hours were required for 41 iterations to reach 0.001 normalized residual error, and two hours were required for calculating 1201 points of bistatic RCS}. A good agreement between the calculations and the Mie-series solution was observed. The RMS error was 0.30 dB for all 1201 points for θ varying from 0° to 120°.
A computer code, named FISC (Fast Illinois Solver Code), has been co-developed by the Center for Computational Electromagnetics, University of Illinois, and DEMACO [13-8]. FISC [13-9] is designed to compute the RCS of a target described by a triangular-facet file. The problem is formulated using the Method of Moments (MoM), where the Rao, Wilton, and Glisson basis functions are used. The resultant matrix equation is solved iteratively by the Conjugate Gradient (CG) method. The Multilevel Fast Multipole Algorithm (MLFMA) is used to speed up the matrix-vector multiply in the CG method.

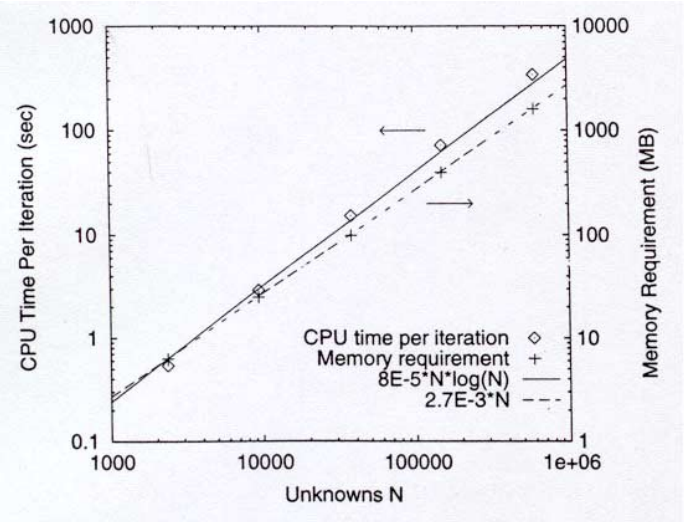


Figure 13-1 : The CPU time per iteration and memory requirements (points) as functions of the number of unknowns for FISC. Two curves, $8\text{x}10^{-5}$NlogN and $2.7\text{x}10^{-3}$N, are also plotted for comparison [13-9].

Domain decomposition method

The EMC analysis of a complex structure leads, in most cases, to prohibitive computation time and/or memory requirements. The principle of the proposed method [13-10, to 13-14] is to decompose the complete problem into a set of smaller problems, which interact only through a limited number of interfaces. In each sub-domain we solve series of boundary-value problems which completely parametrize the behaviour of the sub-domain as far as the field relations on the interfaces are concerned. This parametrization can be put in the form of an interface admittance operator or an interface scattering operator.

This technique has a lot of advantages such as :

- A change in one of the sub-domain necessitates only the recalculation of this particular sub-domain,
- One can use different numerical methods adapted to the particular sub-domain problem.

However, the gain in efficiency is interesting only when the number of unknowns on the interfaces is small compared to the number of unknowns of the original problem.

Using 3D codes coupled with a transmission line code, this technique has been used with success to predict electromagnetic coupling on cable bundles located in complex 3D structures [13-15 to 13-20].

Conclusions

Various methods for efficiently solving electromagnetic problems have been described. A fundamental description of each technique and an overview of the types of problems they are best suited to analyze have been presented. References have been provided that direct the reader to more detailed information and sources of computer codes.

The state-of-the-art in numerical modeling is progressing rapidly. Each year new types of problems can be analyzed. Implementation of these techniques are getting more accurate and powerful.

Computational techniques for solving electromagnetic wave scattering problems involving large complex bodies and for analyzing wave propagation through inhomogeneous media have been intensely studied by many researchers in the past. This is due to the importance of this research in many practical applications, such as the prediction of the Radar Cross Section (RCS) of complex objects like aircrafts, the interaction of antenna elements with aircraft and ships, the environmental effects of vegetation, clouds, and aerosols on electromagnetic wave propagation, the interaction of electromagnetic waves with biological media, and the propagation of signals in high-speed and millimeter-wave circuits. The recent phenomenal growth in computer technology, coupled with the development of fast algorithms with reduced computational complexity and memory requirements, have made a rigorous numerical solution of the problem of scattering from electrically large objects feasible. These numerical techniques involve either solving partial-differential equations with the Finite-Difference Method (FDM) or the Finite-Element Method (FEM) which result in sparse matrices, or integral equations which are converted into dense matrix equations using the Method Of Moments (MOM). To reduce the computational complexity of such computational techniques, especially for large-scale electromagnetic problems, several powerful solvers have been developed. Among these solvers, iterative solvers are ubiquitously used to solve both differential and integral equations. Iterative solvers, in general, require less memory storage, and exhibit reduced computational complexities when compared to direct solvers. Hence, they portend an important method for large scale computing.

For surface structures, there exists no direct solver with reduced computational for efficiently solving the integral equation of scattering. Therefore, one resorts to an iterative solver whereby the computational complexity of a matrix-vector multiply can be reduced. Many methods for expediting matrix-vector multiplies have been proposed, but the Fast Multipole Method (FMM) and its variants hold most promise in providing a fast method that applies to scatterers or arbitrary geometry.

Even though a matrix-vector multiply for scattering problems only require O(NlogN) operations both for volume scattering and surface scattering problems, the number of iterations needed remains unpredictable. Therefore, preconditioning techniques for reducing the required number of iterations in iterative methods are urgently needed in solving electromagnetic wave scattering problems. Finally, even though direct solvers with reduced computational complexities are available for volumetric scattering problems, no such solvers exist for surface scatterers, except for collinear (or almost coplanar) structures. Hence, this remains an open problem for researchers in the future.

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2.3 Test Techniques and Present Limitations

EMC Test on aircraft shall be conducted to verify that the overall system is electromagnetically compatible among all subsystems and equipment within the system and with environments caused by electromagnetic effects external to the system. Moreover margins shall be provided based upon system operational performance requirements, tolerance in system hardware and measurements uncertainties. The paper describes the test facilities utilized to perform conducted and radiated system tests generating potential internal and external electromagnetic disturbances and determining safety margins.

INTRODUCTION

An all electric aircraft could have remarkable benefits in terms of weight and maintenance costs with respect to aircraft that use hydraulic and pneumatic controls; however they present major concern about potential susceptibility problem of its electronics controls to conducted and radiated electromagnetic signals. In testing modern aircraft a major objective is aimed to developing techniques and tests methods for assessing the survivability in the electromagnetic environment of externally generated high intensity radiated field (HIRF) and internally generated radiated or conducted emissions.
System level tests are conducted with the cause-effects technique. A cause generated by an emissive source produces an effects which properly monitored allows to define whether a susceptibility exists. In EMC system definition it’s necessary to establish:
modes of operation
activation of internal and external emissive sources
monitoring methods and techniques

The most common approach is to monitor subsystem performance through visual and aural displays and outputs because it is usually undesirable to modify cable and electronics to monitor signals. However this approach in not quite acceptable because it does not generally allow to determine safety margins which are essential for safety critical subsystems. In addition to taking into account tolerance in system hardware and uncertainties involved in verification of system level design requirements safety margin demonstration is necessary to guarantee system performances with regard to system hardware variabilities due to yield spread and system aging.

SAFETY MARGIN

Suitable monitoring methods shall be adopted to detect system malfunctions following the activation interference sources. Several issues shall be taken into account:
the use of suitable measuring instrumentation which do not alter the value of parameter under examination and at the same time are not affected by the interference generated by the emissive sources
the selection of parameters to be monitored which are meaningful of system performances and can be measured in a quantitative manner
the definition of the detection criteria capable of discriminating the variation of the parameter under test due to interference source from those ones produced by thermal or environmental effects
The last issue is covered by the safety margin interpretation.
Three different safety margins can be identify with the understanding that they imply specific test methods:
Comparison Safety Margin (CSM)
EMC Safety Margin (ESM)
Performance Safety Margin (PSM)

CSM:
The CSM, as the name implies, is based upon the possibility of exploiting the similarity between equipment and system tests. If in system tests the emission test signal of amplitude d is measured and is comparable with the susceptibility equipment test signal s the CSM is expressed as s/d. The term “comparable” implies the same electrical characteristic of the signals and the same coupling paths.

ESM:

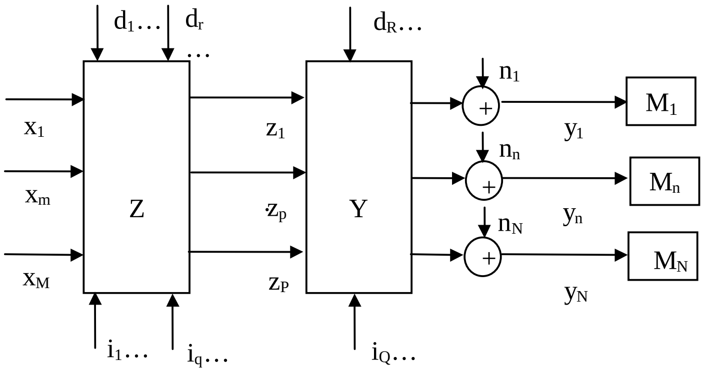


Fig.1

MIL-STD-464 (18 March 1997) specifically requires this type of comparison. In that document it is stated that “past experience has shown that equipment compliance with its EMI requirements assures a high degree of achieving system level compatibility. No conformance to EMI requirements often leads to system problems”. In the same document it is noticed that the “D” revision of MIL-STD-461 and MIL-STD-462 emphasize testing techniques which are more directly related to measurable system level parameters. For instance bulk cable testing is being implemented for both damped sine transient waveform and modulated continuous wave. It is stated that the “measured data from these tests can be directly compared to stresses introduced by system level threats. This philosophy greatly enhances the value of the results and allow for acceptance limits which have credibility”.
The following test amplitudes at system and equipment level are comparable:
the disturbance at the power supply input terminals of the equipment installed in the system and the susceptibility signal injected at the same terminals at equipment level
the common mode system conducted emission measured on a cable bundle and the common mode equipment conducted susceptibility signal injected on the same cable bundle.
When the similarity between the coupling mechanisms at equipment and system level does not exist the CSM test method cannot be used without making large error.
A typical situation exist when comparing radiated susceptibility equipment tests with radiated emission system tests. The test environments are completely different and therefore it becomes impossible to make any comparison.

In Fig.1 the block diagram of a complex aircraft system is shown. The block Z represents the interface to the external world identified by the parameters $\underline{x}=[x_1\ldots\ldots x_M]^T$ detected and measured by on board sensors (aircraft position and altitude, speed, positions of targets and threats and so on). The input data are processed by the aircraft systems as internal parameters $\underline{z}=[z_1\ldots\ldots z_P]^T$ available only from the on board computers and as
external parameters $\underline{y}=[y_1\ldots\ldots y_N]^T$ corrupted by noise $\underline{n}=[n_1\ldots\ldots n_N]^T$ available to the pilot and presented on various cockpit displays and monitors. In system immunity tests the susceptibility signals $\underline{i}=[i_1\ldots\ldots i_Q]$ (internal environment) and $\underline{d}=[d_1\ldots\ldots d_R]$ (external environment) define the radiated and conducted electromagnetic environment required to asses the aircraft vulnerability. They may be generated by external transmitters, on board transmitters, by the activation of on board emissive devices which can operate continuously or in transient conditions. Susceptibility signals may be time dependent, in any case they are deterministic. The repeatability of immunity tests depends on the repeatability of the electromagnetic environments where the aircraft is tested.
The following system transfer function can be identified:

$\underline{z}=H(\underline{x}, \underline{d}, \underline{i})$
$\underline{y}=G(\underline{x}, \underline{d},\underline{i})$

The reference test conditions are achieved where the external interference sources are at the minimum level (environment level $\underline{d}_{min}$) and the internal sources are at the minimum levels (minimum number of operative equipment $\underline{i}_{min}$):

$\underline{z}_{min}=H(\underline{x}, \underline{d}_{min}, \underline{i}_{min})$
$\underline{y}_{min}=G(\underline{x}, \underline{d}_{min}, \underline{i}_{min})$

Assuming that external interference can be artificially changed until the system tolerance interval extreme $\underline{a}$ ($\underline{b}$) of $\underline{z}$ ($\underline{y}$) is achieved:

$a=H(x, d_a, i_{min})$; $b=G(x, d_b, i_{min})$

we can state that ESM is d_a/d_{min} (d_b/d_{min}).
This test method is not always applicable because of the electrical and physical constraints of the system.
Typically the ESM is measured in the following way: the conducted interference on cable bundles connecting the equipment to the system are measured ($\underline{d}_{min}$) and reinjected with a value corresponding to $\underline{d}_a$ ($\underline{d}_b$). Basically the ESM is a safety margin which we can determine by performing susceptibility tests at system level; this approach is not always possible because there is the risk of upsetting the system in an unrealistic manner.

PSM

The PSM specifies the most meaningful test method because aims at the verification of the actual system performances. In the past system susceptibilities were monitored on the display M_1……M_N (Fig.1); the pilot has the task of establishing the presence of a susceptibility on the basis of a purely subjective evaluation. With the advent of more integrated system completely controlled by on board computers it becomes possible to measure the output parameters:

$\underline{z}=H(\underline{x}, \underline{d}, \underline{i})$; $\underline{y}=G(\underline{x}, \underline{d}, \underline{i})$

The PSM can be determinated by means of two techniques.:
desensitization: it consists in changing the transfer function H(G) making the system more sensitive to the wanted signal:

$\underline{z}_a=H_a(\underline{x}, \underline{d}, \underline{i})$; $\underline{y}_a=G_a(\underline{x}, \underline{d}, \underline{i})$

in the test of EEDs (Electroexplosive devices) the actual EEDs are substituted by more sensitive devices capable of detecting signals 20 dB lower than the nominal no fire level
minimum S/N: it consists in reducing the input signal $\underline{x}$ in order to make the equipment (typically a receiver) operate at the minimum S/N level.

$\underline{z'}_a=H(\underline{x}_{min}, \underline{d}, \underline{i})$; $\underline{y'}_a=G(\underline{x}_{min}, \underline{d}, \underline{i})$

MONITORING TECHNIQUES

As it has been said safety margins imply specific practical monitoring techniques. In the following the most commonly used ones are described

2.3.1 Electro-Explosive Devices (EEDs)

Radiofrequency fields can induce currents in the electrical cables of the EEDs. Since such currents can produce the EED activation it is important to determinate their magnitudes even at very high frequencies by measuring the temperature rise of the EED bridgewire corresponding to the Joule heating. The method, which is currently used nowadays, is based upon the Fluoroptic Thermometry sensor .

The sensor in the Fluoroptic Thermometry sensor is a photo-luminescent material (phosphor) whose afterglow varies with temperature. More specifically the time constant of the exponentially decaying fluorescence following pulsed excitation by a flash lamp decreases with increasing temperature. The phosphor, which can be coated directly onto the bridgewire, is coupled optically with both the exciting source and a photo-detector by a single optical fiber. The rate of decay of the fluorescence is determined by monitoring the signal from the photo-detector. The decay time is then converted to temperature by reference to a digital look-up table. Since both the sensing and data communication are optical, no extraneous electrical conductors are required in the system under test or in the surrounding high field environment.

There are two basic methods for measuring surface temperatures of a solid, namely the contact and the non contact methods. The contact method involves the use of a fiberoptic probe with the luminescent sensor powder dispersed in an optically clear binder attached to the end of the optical fiber. The probe tip is placed in contact with the surface to be measured. The non contact method requires that the surface of interests be coated with the phosphor powder/binder mixture and that an open ended optical fiber be used with or without the aid of a lens or special fiber tip tapering to couple the phosphor optically to an instrument located some distance away. There are two important advantages of the non contact method over the contact method for the measurements of low level induced currents via resistive heating:

it eliminates the heat sinking effect (thermal loading) due to the optical fiber since only the phosphor sensing layer is attached to the resistive conductor

it makes the alignment of the fiber tip with the typically small conductor much easier to achieve

The proposed measuring equipment is Model 790 Fluoroptic Thermomether by Luxtron. One disadvantage of this type of measuring system is the low response time of sensor which is about 250ms.

One alternative system utilized another technique named Coloroptic (TM by Metricor); light supplied to the sensor from a LED source is modified at the sensor tip and reflected back along the same fiber to a detector. The color or spectral makeup of the reflected light is modified in proportion to the parameter being measured i.e. temperature or current. The instrument then electro-optically translates the data and displays it. The proposed measuring equipment is Model 1420 EMC Test System by Metricor. With this equipment it is possible to achieve a better response time which is in range of less than 10ms. The main disadvantages of this system is that the EED bridgewires shall be substituted by a proper sensor device, while in the previous method the actual EED bridgewire is used.

The final decision of the system utilize will be based upon the actual characteristics of the chosen EED, which shall be characterized as specified in [3] according to:

Method 2204: Radiofrequency impedance
Method 2207: Radiofrequency sensitivity
Method 2205: Static discharge sensitivity

Moreover in order to be able to verify the response to transient disturbances (such as lightning induced currents for example) it is necessary to measure the thermal time constant of the EED.

2.3.2 MIL-STD-1553 B (Data bus Monitor)

The data bus is the natural source of information to perform EMC system testing. In the MIL-STD-1553 B bus a bus analyzer is connected to a coupler box to monitor the bus traffic. When a wrong parameter causes a system failure, even if caused by interference the malfunction is fixed as a system failure. The aim of EMC system testing is to determinate the safety margin when there are no evident malfunction.

When testing a digital system monitoring the parameters of the transmitted waveforms has little meaning if the waveform distortion does not cause a wrong output data; additionally the wave distortion is not easily related to a safety margin. The proposed test procedure is as described in the following.

The test procedure is divided in two parts: system characterization and measurements. During system characterization the parameter under test is measured in condition of minimum interference, which means the minimum number of equipment/subsystem activated. The parameter is measured as multiples of the LSB (Least Significant Bit). For example we assume the case of an angular value comprised between –180 and +180 degrees with increments of 1 LSB=0.01098 because of 16 bit quantization. In the following table the characterization of the angle measured with 1183 samples is shown.

Numerical values of the parameter	Statistical frequency (f_i)	Deviation (s_i)
39.50650	9	-4
39.5170	50	-3
39.5280	152	-2
39.5390	303	-1
39.5500	420	0
39.5609	238	1
39.5719	11	2
total	1183	

One measures the deviation s_i from the value with the highest statistical frequency f_i=420 samples. It is assumed that the probability density of the parameter under test is Gaussian; therefore in order to get a characterization of the parameter statistic it is necessary to determine the mean value and the standard deviation, which are calculated as follows:

$$S_m = \sum_{i=1}^{N} \left(\frac{f_i s_i}{N} \right) = -\frac{533}{1183} = -0.45505\ LSB$$

$$\sigma = \sqrt{\sum_{i=1}^{N} \frac{f_i s_i^2}{N} - S_m^2} = 1.1435\ LSB$$

From the theory random variables it is known that 93.73% of the measurements fall within the interval

$$V_{s^-} = S_m - 3\sigma \qquad V_{s^+} = S_m + 3\sigma$$

We assume that M_i and M_s represent the largest possible values still acceptable according to the manufacturer specification even if they are outside the statistical tolerance interval.

When the interfering subsystems or the external environment are activated the parameter under test changes assuming the values V_{i^+} or V_{i^-} .

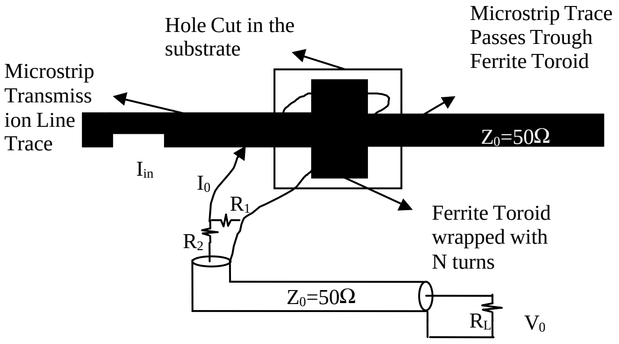


Fig.2(a): Physical topology

The PSM is calculated as:

$$PSM_+ = \frac{V_{i^+} - V_{s^+}}{M_s - V_{s^+}}$$

$$PSM_- = \frac{V_{s^-} - V_{i^-}}{V_{s^-} - M_i}$$

These safety margins are based upon the actual performances of the system. They have been proven to be very accurate and sensitive highlighting malfunctions which do not appear during functional tests. The only drawback is represented by the need of a processing with a large mass memory in order to be able to collect a large amount of data.

MIL-STD-1553 B (Interference direct drive)
Efforts to determine and quantify the susceptibility and vulnerability of avionic system and subsystem components to electromagnetic interference (both intentional and unintentional) according to the ESM method typically include the need of direct driving interference signals. In order to inject signals on the 1553 data bus [4] is necessary to develop a suitable breakout box, which must have the following circuits:
Current sensor circuit
Voltage sensor circuit
Signal injection probe circuit

Current sensor circuit

The current sensor is located downstream of the direct injection point . Fig 2(a) illustrates the topology of the current sensor.

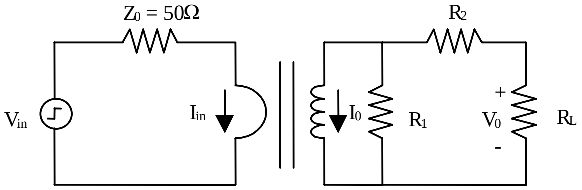


Fig.2(b): Equivalent electrical circuit used to drive the current sensor transfer function (Z_c)

It is composed of a ferrite core wrapped with N turns which form the secondary winding. The sensed line passed through the centre of the core and comprises the primary winding. A resistor network (R_1 and R_2), the cable characteristic impedance and the cable termination R_L load the secondary winding. The core is mounted in a rectangular cutout in the board and the ground plane is removed in region of the cut-out to accommodate the core. The equivalent circuit for the current sensor is shown in Fig.2(b).
The transfer impedance is defined as the ratio of the (sensor) output voltage V_0 to the monitored line current I_{in}:

$$Z_C(\omega) = \frac{V_0}{I_{in}} = j\frac{\alpha R_L \omega}{N\left(j\omega + \frac{\alpha(R_2+R_L)}{L}\right)}$$

where N is the number of turns on the current sensing toroid, ω is the angular frequency, L is the secondary winding self inductance and $\alpha = \dfrac{R_1}{R_L + R_1 + R_2}$

The inductance L is given by:

$$L = \frac{\mu_0 \mu_r N^2 W}{2\pi} \ln \frac{b}{a}$$

where $b(a)$ is the outer (inner) radius of the magnetic material, $\mu = \mu_0\mu_r$, is the permeability of the core and $W = b - a$ is the current probe width.
The high frequency asymptotic limit of the transfer impedance is:

$$Z_C^{HF} = \frac{\alpha R_L}{N}$$

while the low frequency asymptotic limit is:

$$Z_C^{LF} = j\frac{\omega R_L N\mu_0\mu_r W \ln\left(\frac{b}{a}\right)}{2\pi\left(R_L + R_2\right)}$$

The reflected impedance of the sensor (the series impedance) introduced in the sensed line due to the presence of the sensor given is given as:

$$Z_{\mathrm{Re}\ f} = \frac{R_{\sec}}{N^2}$$

where R_{sec} is the total secondary impedance composed of the series and parallel combinations of R_1, R_2 and R_L. Finally the 3dB frequency is given by:

$$f_{3dB} = \frac{1}{2\pi}\frac{\alpha\left(R_2 + R_L\right)}{L}$$

It is the frequency where the sensor response declines by $1/\sqrt{2}$ of the maximum magnitude of the transfer impedance.

The current sensor transformer is constructed of C2050 ferrite cylindrical core (*a =0.235cm, b =0.480cm)* with a nominal relative permeability $\mu_r = 50$ at *100 MHz.* The current sensor design utilized N =3 turns on the secondary, resistance values of $R_1 = 100 Ohm$, $R_2 = 0 Ohm$ and $R_L = 50 Ohm$ (cable impedance).

Voltage sensor circuit

The voltage sensor probe circuit is a capacitively isolated voltage divider:

The circuit and components are shown in Fig .3(a). For this application the ability to monitor all the traffic on data bus line required, but the isolation of the probe from any DC components on the line is necessary.

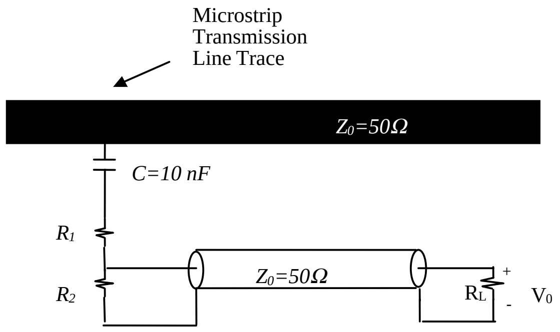


Fig.3(a): physical topology

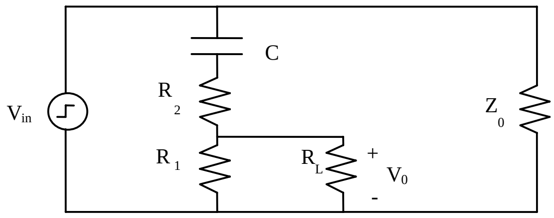


Fig.3(b): Equivalent electrical circuit used to derive the voltage sensor transfer function

From the equivalent circuit shown in Fig.3(b): the transfer function for the voltage sensor circuit is:

$$Z_V(\omega) = \frac{V_{out}}{V_{in}} = j\frac{\omega C\gamma}{1 + j\omega C(R_1 + \gamma)}$$

where γ is the parallel combination of the sensor cable impedance and *R₂*. The 3 dB break point of the circuit is given by:

$$f_{3dB} = \frac{1}{2\pi}\frac{1}{C(R_1 + \gamma)}$$

and is the frequency where the output voltage is down by $1/\sqrt{2}$ of the high frequency asymptotic value.

The monitor must be sensitive to frequencies characteristic of the 1553 bus. This consideration leads to the selection of the following component values:
$C = 10nF$ (rated to 100 V), $R_1 = 1kOhm$, $R_2 = 50Ohm$, and $R_L = 50Ohm$ is the cable impedance. These values result in a break point frequency of 15.5kHz.

Signal injection probe circuit

The signal injection circuit capacitively couples the direct drive signal to the driven transmission line.

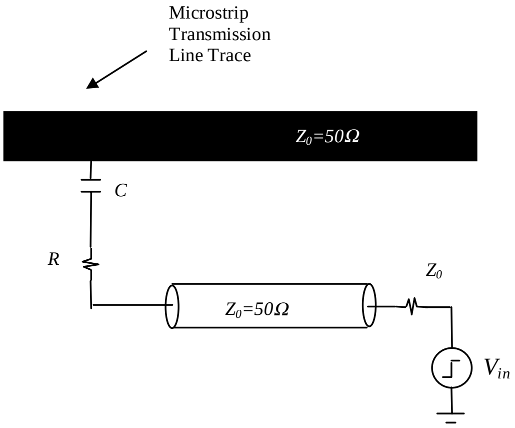


Fig. 4(a): Topology and physical layout

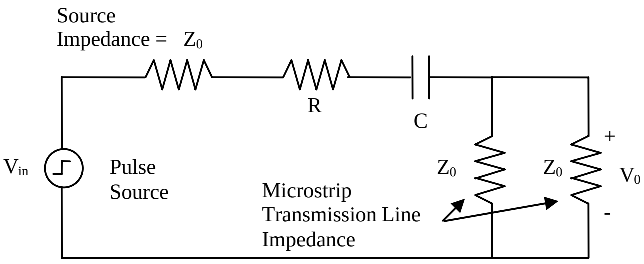


Fig. 4(b): Equivalent circuit used to derive the injection circuit transfer function (Z_I)

To prevent reflection in the power divider circuit when attached to the driven trace, it is also designed to terminate the drive signal in a match load. Fig. 4(a) depicts the topology of the signal injection circuit and Fig. 4(b) shows its equivalent circuit.

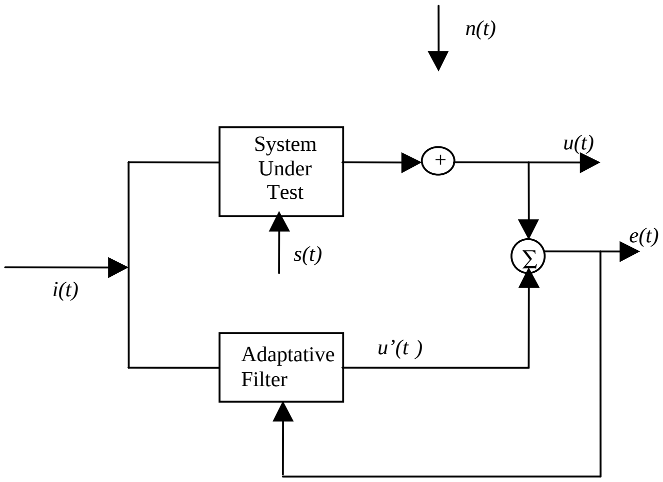
The capacitance and resistance values of the drive signal injection circuit are chosen to:
provide maximum coupling efficiency of the drive signal to the transmission line DC
isolate crosstalk between to transmission line traces
provide a matched impedance to the drive circuit when it is attached to a transmission line trace
The transfer function of the signal injection circuit is given by:

$$Z_I(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = j\frac{\omega C Z_0}{1 + j\omega C(1.5Z_0 + R)}$$

where the microstrip transmission line is assumed matched terminated on either side.
Consideration of the above issues leads to the selection of the following components values :
C =62pF and *R = 25Ohm.*

Identification Technique

Susceptibility tests are carried out by taking into account the correlation between the susceptibility signal and the malfunction of the system, which is generally monitored with manual and/or visual methods. The use of automatic monitoring system could greatly improve the accuracy of susceptibility tests which should address susceptibility signals. In Fig. 5 a general schematic of the proposed approach is drawn:



where
i(t) and *u(t)* are the input and output signals of the system under test
n(t) is the random noise
u'(t) is the output of the adaptive filter
e(t) = u(t) – u'(t) is the error signal
s(t) is the susceptibility signal which can generate by an internal or external source

The adaptive filter is regulated by a suitable identification algorithms which estimate the parameters of the system under test in the absence of the interference signal *s(t)*. When the error *e(t)* is minimum the adaptive filter identifies the performance of the system under test. The interference source is activated and any susceptibility effects is monitored as a change of the error *e(t)*. In this manner the malfunction can be evaluated in a quantitative manner. Obviously the complexity of the identification system can go from a very simple device when one wants to monitor a steady state signal to a very complex unit when a dynamic system shall be controlled. A simple example of the proposed method is shown in Fig 6 where the parameters of a sinewave (amplitude, frequency, and phase) shall be monitored:

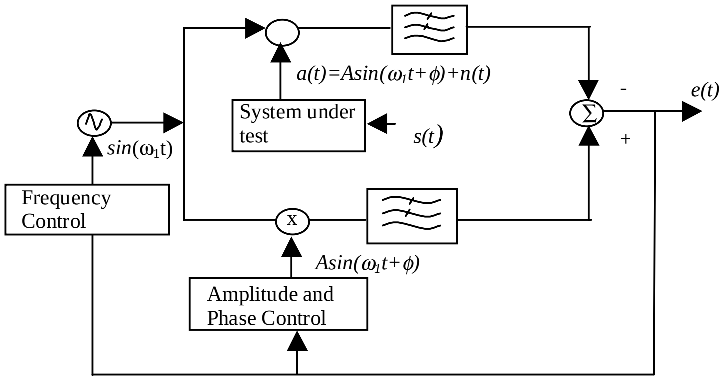


Fig.6

In the two branches of the system two correlations systems are used: in the upper branch the signal *a(t)* of the system under control shall be monitored, in the lower branch the same signal is

generated by an adaptive control algorithm.

When the susceptibility signals *s(t)* is activated any change in *A*, ω_1 and ϕ are detected as a change of *e(t)*. Moreover by means of the adaptive algorithm it is possible to pinpoint which parameter was effected.

TESTS SEQUENCE

In the previous paragraph the main issues of EMC system testing have been examined. During the test sequence the following points will be considered:

full coverage of operative modes

selection of representatives test conditions

performance of tests in the most favourable testing situations

It is essential to verify the following conditions:

avionic EUT input and output signals from the other stages and/or from EDSE are properly simulated

the reduced shielding effectiveness due to the lack of part of the structure does not impair the validity of test results

suitable simulations are carried out to determinate the levels of interfering signals to be injected on the structure in the presence of external electromagnetic sources (Lightning and High Intensity Radiated Field (HIRF))

Both EMC intersystem and intrasystem testing are actually identified by two types of tests-electromagnetic hazards and electromagnetic effects. In both cases the EEDs or squibs are instrumented to sense a heat rise in the bridgewires; moreover the control functions of the system are monitored to determinate degradation or system reliability according to the Safety Margin.

The internal device shall be operated according to their actual operatives modes in ground and flight conditions. The test sequence shall be defined on the basis of the capabilities and performances of EGSE. The activation of internal devices generates the background interference, which is

due to the spurious coupling of wanted signals. The test sequence includes the following phases:

activation of external and internal interference sources

monitoring of the parameters which are considered representative of system performances

Both activation and monitoring operations are required to prepare the EMC Test Matrix which defines the actual test sequence.

In addition to interaction tests also bonding resistance and isolation measurements will be performed.

ACTIVATION

The activation comprise the execution of all those operations which are performed to perform the wanted mission and additionally those operations due to external sources which may be wanted such as external transmitter emissions or unwanted such as lightning.

<u>External electromagnetic sources</u>
The external sources are simulated according to two test procedures:
Low Level Coupling / Field Testing
High Level Testing based on Modelling and / or Coupling Data

Low Level Coupling / Field testing
This procedure has the main purpose of defining the transfer function E field / induced current inside the aircraft; it shall be conducted together with numerical and analytical investigations. The first point is to start with analytical interference assessment regarding the most critical frequencies the aircraft does respond best according to its design like structure, slots and so on followed by a numerical simulation of the surface currents and the surface charges as a response to an electromagnetic field depending on the field parameters like frequency polarization, field strength and angle of incidence. Experimental investigations are conducted on the not powered system at a simulated phase

The investigations on the not powered system determine the transfer function from the outer field as well as from the surface currents to the internal field and to the resonances and induced currents on different signal wirings.
The tests with the not powered system are distinguished between field radiation and direct injection tests of the electric and magnetic field equivalent.
These investigations are helpful and necessary to limit the investigation efforts at live system tests where concentration of the tests runs is based on the information received from the analytical and numerical as well as from the experimental investigations conducted with not powered systems.
The experimental validation can be conducted in the following three manners:
<u>Low Level Direct Drive (LLDD)</u>
This procedure can be used to measure the transfer function at low level between the skin current and the currents on individual equipment wiring bundles. If the relationship between the external High Intensity Radiated Field (HIRF) environment and skin current is known for all illumination angles and polarizations, either by accurate mathematical modelling or use of the Low Level Swept Current (LLSC) test described in the following, this skin current can be set up by direct injection into the aircraft structure (or part of it). The resultants currents on the internal cables are measured with a currents probe and normalized to external unit field strength so that they can be scaled to the appropriate HIRF environment. This test method has improved sensitivity compared with the Low Level Swept Current (LLSC) test. It is best used for frequencies below first structure resonance.
<u>Low Level Swept Current (LLSC)</u>
This procedure, which can be applied up to 400 MHz, is used to measure directly the transfer function between the external field and the aircraft / EUT cable bundles currents. Since the transfer function relates cable currents to the external field, the inducted bulk cable current test levels can be related to an external field.

The structure is uniformly illuminated sequentially from all sides by both horizontally and vertically polarized swept frequency fields,
and the currents induced on the internal cable bundles measured. The ratio of this current to the illuminating field strength is computed and normalized to 1 V/m. This provides the transfer function in terms of induced current per unit external field strength which can then be extrapolated to the required HIRF field strength by multiplying the induced current at 1 V/m by the external HIRF field strength. The extrapolated HIRF currents for all measured configurations for each bundle being assessed are overlaid and a worst case induced current profile produced. These profiles can be compared with the induced current measured during the Bulk Current Injection (BCI) test conducted on a simulation rig, where the actual installation cable bundles are used. The comparison may not show equivalence if there are changes in installation (cable length, screening, bonding and cable composition)

Low Level Swept Field (LLSF)
The test procedure, which is performed at frequencies higher than 100 MHz, is similar to LLSC. The internal fields local to the EUT are measured instead of the cable bundle current and various techniques are used to ensure that the maximum internal field in the vicinity of the EUT is measured.

High Level Testing

This procedure shall be conducted on the live system at either single stage level or a multi stage structure level depending on the configuration and/or capabilities of the EGSE. The guidance and control components with the required wiring are the basis for the data acquisition during the functional response tests with the fully operational system.

The interfering source activation procedure can be conducted in the following manners

High Level Direct Drive Test
It is possible at frequencies normally below the structure resonance to inject high level currents directly into the structure for lightning and external electromagnetic field simulation. It is essential that mathematical modelling predictions or LLSC measurements are made to determine the skin current distribution that will exist for different attachment points and paths (lightning) and for different polarizations and illumination directions (electromagnetic fields) so that these can be accurately simulated during this test. This procedure has the advantage of testing all systems simultaneously but is very restricted on frequency range.

EUT Bulk Current Injection
The purpose of this test, generally conducted at frequencies lower than 400 MHz, is to measure the current at EUT malfunction or test level of the EUT when RF currents are injected onto its wiring via a current transformer. The installed system is tested using BCI with test levels determined from LLDD test or LLSC test. Each bundle in the system is tested by injection and measurement of the inducted current on that bundle. If a bundle branches, then each relevant branch containing wiring of the system under test may need to be tested.

During BCI testing the system shall be fully operational. Simultaneous multi-bundle bulk current injection may be necessary or systems; where for example there are redundant/multi-channel architectures.

High Level EUT Field Illumination
When the internal RF field surrounding the EUT has been measured during LLSF test and extrapolated to that which would exist if the aircraft was in the HIRF environment, then the EUT can be illuminated in this field by localized internal illumination. This is providing that the radiating antenna if far enough away to ensure that the total volume of the EUT and at least half a wavelength of the wiring is simultaneously and uniformly illuminated during testing.

High Field Illumination
This procedure relies on being able to generate HIRF fields external to launch vehicle. Below 400 MHz the overall system shall be uniformly illuminated. Above this frequency the illumination can become more localized to the EUT providing that all parts of the EUT are illuminated and as a minimum at least 1 wavelength of associated wiring should be uniformly illuminated to the field.

For frequencies below 400 MHz the launch vehicle (or an isolated stage) is placed at sufficient separation from the radiating antenna to ensure uniform illumination. It is illumined an all sides and for both horizontal and vertical polarization.

The peak field shall be modulated with realistic modulation types. The field is calibrated by measuring the field in the centre of the test volume prior to the placement of the launch vehicle. The EGSE necessary to monitor possible malfunctions shall be located in areas where no susceptibility problems can occur.

CONCLUSIONS

The application of state of the art technologies has taken to the design an development of test facilities which are suitable for the performance of all EMC / HIRF tests that are necessary to obtain aircraft qualification according to military standards or customer requirements.
In particular, the objective of performing accurate HIRF testing on the whole aircraft has been achieved

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B.Audone – *Compatibilità elettromagnetica,* McGraw-Hill, 1992
S.Ripamonti – *Articolo:'HIRF /EMC Test Technologies and Methodologies'*
MIL-STD-1576 – "*Electroexplosive Subsystem Safety Requirements and Test Methods for Space System*" July 1984
C.Courtney and alias – "*Breakout Box Experiments of Electromagnetic Susceptibility of Aircraft Electronics*" IEEE on EMC November 1996

3. APPLICABLE STANDARDS FOR MILITARY SYSTEMS

Standards/Specifications are important means for (military) systems including electrical/electronic equipment to achieve Intra-System Electromagnetic Compatibility and to protect them sufficiently against electromagnetic environment effects like e.g. “High Intensity Radiated Fields (HIRF)”, Lightning, HPM or Electromagnetic Pulse (EMP).

Standards/Specifications will specify the electromagnetic environment parameters to be considered, they include requirements on equipment and sometimes system design, they should define procedures, how to demonstrate sufficient protection. They also should keep in mind how to guarantee sufficient protection during service time of the system.

This chapter deals with an analysis of the existing Standards/Specifications which are mainly applied by NATO respectively which might be applicable for the military systems.

3.1 Electromagnetic Effects to be Considered

The following electromagnetic effects will be considered in this document:

Intra-System Electromagnetic Compatibility

It means Electromagnetic Compatibility between all electrical/electronic equipment installed in a system including the transmitters and receivers.

Intra-System EMC is the absolute preposition for the function of a system.

High Intensity Radiated Fields (HIRF)

HIRF describes the electromagnetic field strength environment, which can be expected from external transmitters like broadcast, radar, or transmitters on other systems.

Lightning

Protection against natural lightning is required for different systems.

It includes :

- Effects on structure/structure components (“direct effects”) and
- Effects on electronic systems/equipment (“indirect effects”)

Electromagnetic Pulse (EMP)

It will be generated in nuclear explosions.

Two different types of pulses can be defined :

- the Exo-atmospheric EMP :

The explosion takes place in higher altitudes. The only effect is the EMP. It is generated in an area only limited by the horizontal conditions. It is defined as a constant threat for this whole area.

- the Endo-atmospheric EMP :

The event takes place near the surface. The EMP is one of different other nuclear effects. The amplitude is dependent on distance. The pulse is generally wider

Only the Exo-atmospheric pulse is considered in this document, because it is the more likely threat.

E- and P-Static

Caused by vibration, influences of the environment (“e.g. dust”) systems or parts of them might charge up to extreme potentials. – Discharge might cause damage to electronic, personnel shock, ignition of fuel and interference.

HPM (“High Power Microwaves”)

High Power Microwaves are likely to become a significant future threat. Extreme high fields might be generated by special weapons to damage RF-sensors (“front door effects”) but also non-antenna equipment like computers, etc (“back door effects”) of weapon systems depending on electrical/electronic systems.

The following areas are not considered in this document:

Electromagnetic Spectrum Control

Emitted interference of systems; too special

HERF

Hazards of Electromagnetic Radiation on Fuel

3.2 Survey of EMC-Relevant Standards/Specifications Required

Where Standards or Specifications should generally be available, is pointed out in fig. 3.-1. Not included in this figure are management requirements, which are defined in different documents, too.

Environment

Most systems have to work sufficiently in a certain external electromagnetic environment. This can be represented by e.g. HIRF, Lightning, the EMP, HPM or in some cases also by electrically charged-up items/components etc., where the systems or equipment might come in contact with.

The environments are absolutely necessary as a basis for the system design and for system testing, if sufficient protection shall be demonstrated.

Different environments might be applied for HIRF, Lightning and E-Static for different systems depending on their special characteristics and tasks.

Requirements on Equipment

To achieve sufficient protection against the EM-effects, a balanced protection has to be realized in each case between the protection measures on equipment level and the measures, which can be applied on system level (e.g. shielding).

That means, the equipment installed in a system must generally fulfill some requirements with respect to emitted interference as well as with respect to insusceptibility to signals coupled–in.

Standarised test setups and limits have been created to control the EMC-properties of the equipment.

Emitted interference and susceptibilities have to be considered for Intra-System EMC.

Susceptibilities only have to be controlled with respect to the electromagnetic environments. The levels, which will be applied in this cases, correspond to the internal environments which will be coupled-in.

Equipment, which is qualified in accordance with an existing specification/standard, is very helpful for the system designer. It also a preposition, if systems shall be modified.

Requirements on Systems

Significant protection must generally be realized on system level, especially with respect to the external environment. – In principle it is not of interest, how the protection is realized, if the requirements are fulfilled at the end.- It might be a too high grade of specification, too, if equipment and system measurements are specified at same time.

Some general rules, however, should be considered for the design, e.g. about bonding, etc. These can be found in many handbooks, where a lot of experience is concentrated.

System Testing

After having finished the development, it has to be demonstrated, that all requirements are fulfilled and that sufficient hardening is available against the external electromagnetic effects.

Intra-System EMC has to be demonstrated as a basic requirement and protection against HIRF, Lightning, EMP and HPM as required. In some rare cases it might also be necessary to make system measurements with respect to E-Static (e.g. charging up a complete aircraft).

A lot of technical problems and uncertainties can be involved just into system measurements with respect to external effects like HIRF, Lightning, HPM and sometimes EMP. The real threat can generally never be completely simulated as well as all threat cases, which might come up in practice.

Agreed and proved procedures should be available.

Maintenance

EM protection measures are more and more involved in system safety aspects. This is applicable for Intra-System EMC as well as for HIRF, Lightning, EMP and E-Static.

Some of the protection measures might become less effective caused by corrosion, damage, etc.

Methods should be available to control EM protection during life time.

Modifications

Many systems will be modified during life time. New or other equipment will be installed, parts of the structure will be changed (e.g. exchange of metallic structure parts against Glass Fiber or Carbon Fiber ones in the case of aircraft). Methods have to be available how to guarantee sufficient protection after such a process without repeating a lot of expensive system testing.

These methods shall cover Intra-System EMC as well as all EM environmental effects.

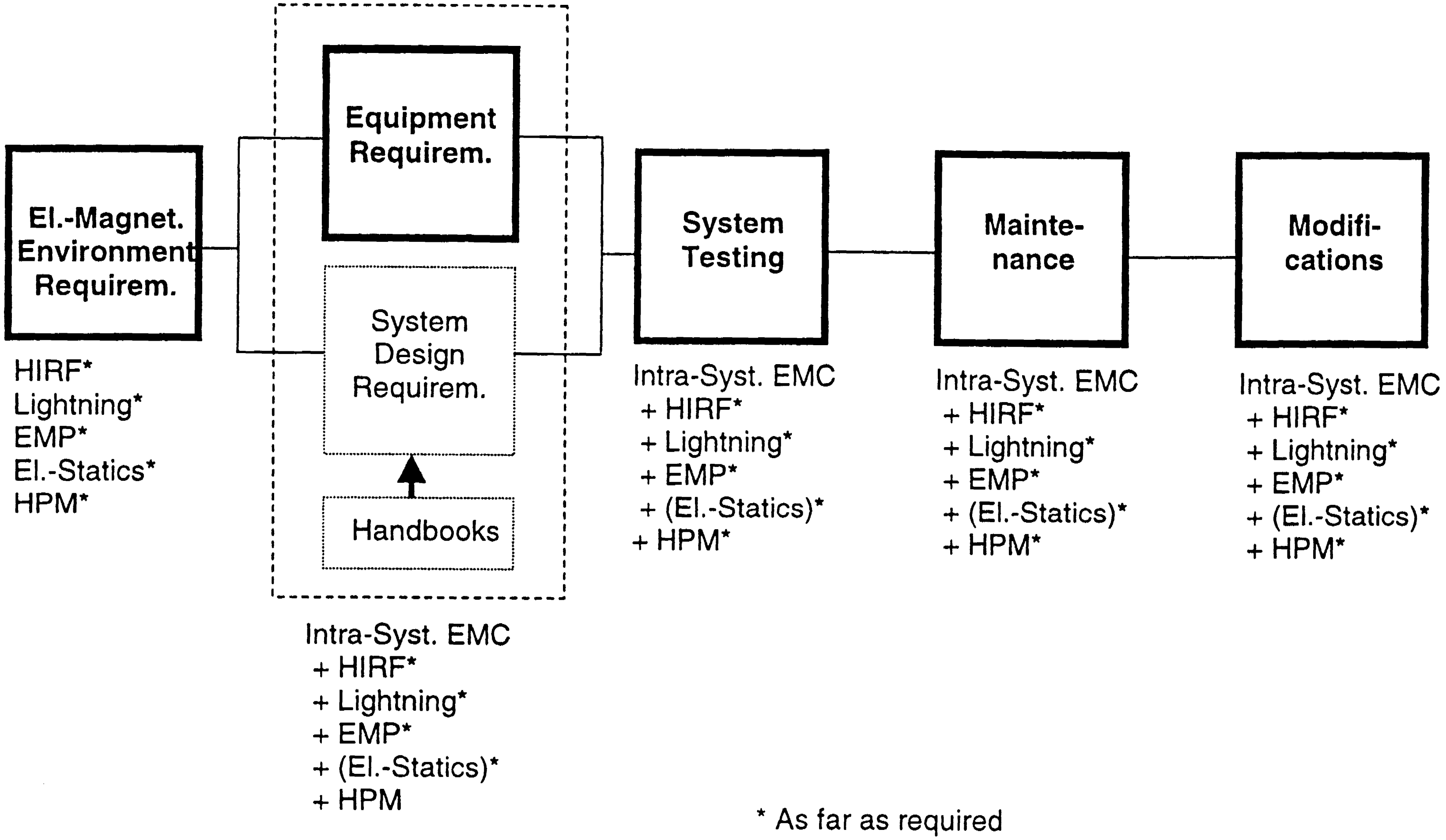


Fig. 3.-1 : Survey of Standards/Specifications Required

3.4 Situation with “Existing Standards/Specifications”

General

The following groups of standards/specifications will be considered :

- STANAGs, created directly for NATO military systems
- MIL-STDs, responsible for military systems in the US, but also in a lot of other countries
- Standards made respectively for modern commercial aircraft :

A lot of work has already been performed by US and European specialists to create new standards to ensure sufficient Lightning and HIRF protection for modern commercial aircraft.

- Standards/specifications for commercial electric/electronic equipment.

Other military standards exist, too, e.g. in Germany the “VG”-Standards or in Great Britain the British Standards. In addition there are some very modern project related EMC standards in Europe, e.g. for the aircraft EUROFIGHTER. - These documents are not considered here.

Intra-System EMC

General

The Intra-System EMC has to be considered as the absolute prerequisite for the function of a system, that means it has to work without any malfunctions also if no outside EM effects are present.

Hardening a system only against the external EM effects will in most cases not be sufficient to achieve Intra-System EMC, too. Different types of interference signals and different coupling paths are involved.

Intra-System EMC will be achieved by controlling all significant EMC interfaces of each individual installed in a system very careful with respect to :

- limitation of interference emitted to the outside
- requiring a certain insusceptibility to signals arriving from the outside

The limits applied in both cases are based on practical experience. In combination with the properties of the system and the usual system design rules (“bonding, cabling, etc”) they guarantee with a good probability the Intra-System EMC.

The EMC properties of an equipment will generally be controlled by tests and limits for the interfaces pointed out in fig. 3.-2.

Applying EMC controlled equipment, however, is not an absolute guarantee for sufficient functioning of a system. System compatibility tests have to be carried out to demonstrate sufficient safety margins (6 to 20 dB) for all functions of interest (at least for safety critical ones, in general also for critical ones). – Interaction testing is generally not sufficient.

The Intra-system EMC can be affected by corrosion, damage caused by vibration, etc. It should therefor be controlled during service-time.

Modifications may also change inside coupling conditions. Care has to be taken after installing new equipment, exchanging parts of conductive structure against poor or non-conductive ones, etc.

Standards/Specifications Required

To achieve and to ensure Intra-System EMC during life time the following standards/specifications shall be available (fig. 3.-1) :

- Requirements on equipment
- Procedures to demonstrate Intra-System EMC including safety margins
- Methods to control Intra-System EMC during life-time (maintenance)

These, however, can be combined with measures to control external EM effects, too.

- Methods for control of Intra-System EMC after modifications

No requirements have generally to exist on design of system. It is in the most cases up to the system designer, how protection will be realized. A lot of guidelines and recommendations, however, is laid down in Handbooks, etc.

Existing Standards/Specifications

A survey of all documents is presented in table 3.-1. – The full titles and the status can be found in the chapter 3.5 : “References”.

STANAG‘s

Requirements on equipment :

Only a few documents exist, however, for the most critical systems. Equipment requirements are available for aircraft (STANAG 3516) and for ships (STANAGs 4435, 4436, 4437). They are in a rework status. – Some requirements on EEDs might be included in STANAG 4238 (in preparation, not available to industry).

Requirements on systems :

One document (STANAG 3659) defines some design requirements for (metallic) aircraft. Another document (STANAG 4567) is in planning, which might also cover some design recommendations. – Some information might also be found in STANAG 4238 (in preparation, not available to industry).

System test procedures :

Procedures for system testing are in a planning status for aircraft only (STANAG 7116). The document might also include some procedures for Intra-System EMC testing.

Maintenance :

A document, which will generally cover maintenance and maybe modifications, too, is in preparation as STANAG 7130.

Modifications :

No special rules exist how to proceed after a modification of a system, that means, how to evaluate the effect of a modification on EMC properties and which tests have to be performed to demonstrate full compliance again.

MIL-STD‘s

Requirements on equipment

With respect to equipment requirements the MIL-STD-461/462 exists, which is generally applied for equipment of all systems.

Some susceptibility requirements can be found in MIL-STD-1512 for EED‘s.

Requirements on systems

Some design requirements for ships and spacecraft can be found in MIL-STD 1310G respectively MIL-STD1541A and MIL-STD-1542B. – The old MIL-B-5087 corresponding to STANAG 3659 is no more applicable. – A lot of guide and information, however, is available in various Handbooks.

System test procedures

No MIL-STD has been found with procedures for system testing.

Maintenance :

There is no document, which handles this field in detail.

Modifications :

No special document is available.

Commercial Aircraft Documents

Requirements on equipment

The EMC requirements for commercial aircraft equipment are laid down in RTCA/DO-160. The procedures are mainly based on old MIL-STD versions.

Requirements on systems :

No design requirements have been found.

System test procedures

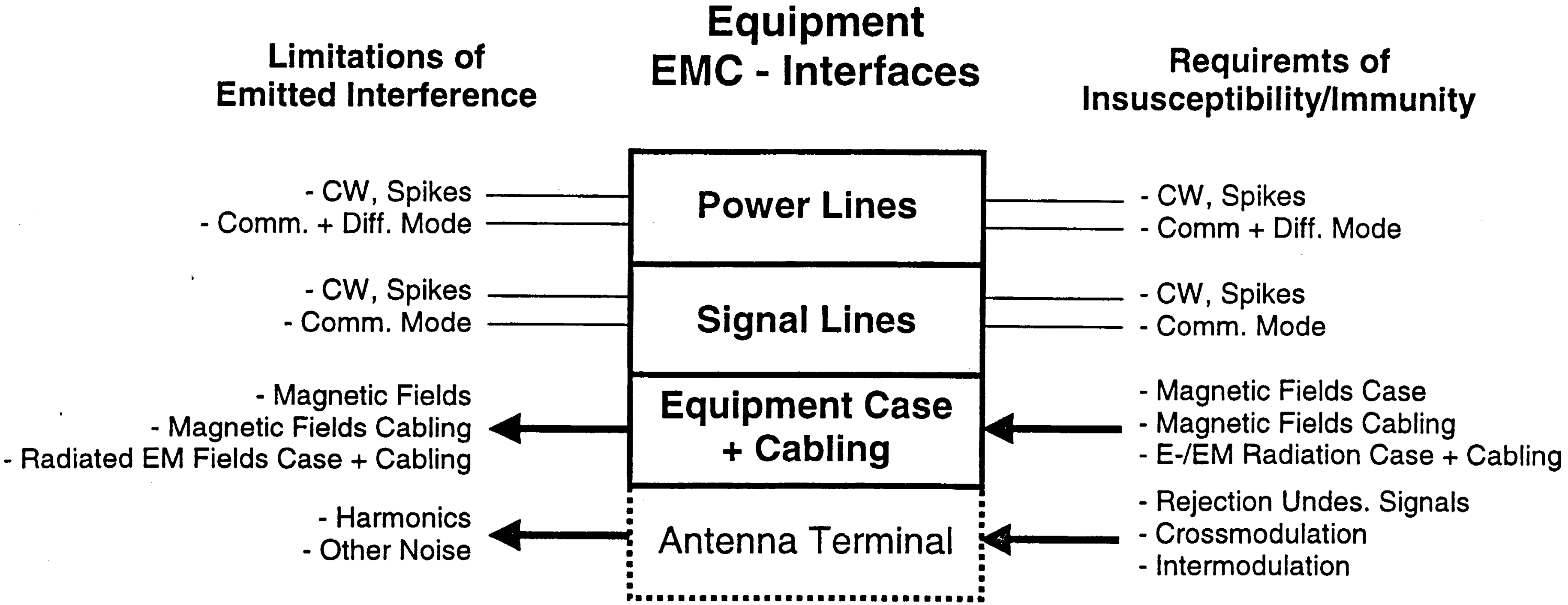
No procedures are defined.

Maintenance :

There will be some information available with respect to HIRF and Lightning Protection. These measures might also be applicable here.

Modifications :

Not covered.



Remark : Control of antenna terminal interface sometimes not included

Fig. 3.-2 : Survey of Test-Set Up's and Limits typically available in EMC-Equipment Specification

	Environment	Requirements on Equipment	Design Requirem. on System	System Test Procedures	Maintenance	Modifications
General	NA	MIL-STD-461D MIL-STD-462D	((STANAG 4567))?		((STANAG 7130))?	((STANAG 7130))?
Munition, Weapon Systems incl. EED‘s	NA	MIL-STD-1512 (EED‘s) (STANAG 4238)?	(STANAG 4238)?			
Military Aircraft	NA	STANAG 3516* MIL-STD-461D MIL-STD-462D	STANAG 3659 (metallic only)	((STANAG 7116))?		
Ships, Surface, Metallic	NA	STANAG 4435* MIL-STD-461D MIL-STD-462D	MIL-ST-1310G			
Ships, Surface, Non-metallic	NA	STANAG 4436* MIL-STD-461D MIL-STD-462D				
Submarines	NA	STANAG 4437* MIL-STD-461D MIL-STD-462D				
Space and Launch Vehicles	NA	MIL-STD-461D MIL-STD-462D	MIL-STD1541A MIL-STD-1542B			
Ground Systems	NA	MIL-STD-461D MIL-STD-462D				
Commercial Aircraft	NA	RTCA/DO-160				
Commercial Other Systems	NA	EN‘s, IEC‘s				

STANAG xxxx : Available to industry as latest edition
STANAG xxxx* : Available to industry not as latest edition

(STANAG xxxx) : Not available to industry
((STANAG xxxx)) : Planning status
? not known if subject is included

Table 3.-1 : Standards/Specifications covering Intra-System EMC

Other Commercial Standards/Specifications

Electromagnetic Compatibility of commercial equipment in daily life or also concentrated in industrial plants will generally be achieved by defining requirements on equipment only.

A lot of documents have been created in the last years for commercial equipment to define test set-ups and limits for all EMC interfaces of interest like pointed out in fig.3.-1.

The test procedures applied are often very similar to the STANAG/MIL-STD ones. In many cases they are better, respectively more modern from the point of EMC.

The limits for emitted interference are comparable, too. Conducted susceptibility requirements are generally lower like in military documents, sometimes, however, they are also higher.

No special standards/specifications have been found with definition of system requirements, system tests, maintenance procedures and modifications.

High Intensity Radiated Fields (HIRF)

General

“High Intensity Radiated Fields” cover the problems, which might come up by the electromagnetic fields produced by radio transmitters, radar stations or transmitters on other military systems.

Modern systems are getting more and more vulnerable to these external fields. The reasons are mainly, that electrical components are getting increasingly involved in also safety critical functions of the systems and that modern structure materials like carbon or glass fiber will generally provide significantly less shielding to these fields. In addition modern electronic components are in most cases more susceptible. More electromagnetic sources might also be found today than in the past.

The area of HIRF is a very modern one. Extended activities took just place in the US and Europe to define suitable environments for commercial aircraft and to create procedures how to demonstrate sufficient hardening.

Standards/Specifications Required

Documents should be available for (fig. 3.-1) :

The HIRF environment

Requirements on equipment

Procedures to demonstrate sufficient protection

Methods to control HIRF protection life-time.

These, however, can be combined with measures to control Intra-System EMC and other external EM effects

Handling of modifications

Similar to Intra-System EMC no requirements have generally to exist on system design.

Existing Standards/Specifications

A survey of the existing situation can be found in table 3.-2.

STANAG‘s

<u>Environment</u> :

A worst case operational EM environment is defined in STANAG 1307 (restricted). An other environment is included in STANAG 4234 especially for weapon systems including EED‘s. STANAG 3614 presents some information (as an example) for military aircraft. – All environments are different. The reason, however, might be, that STANAGs 4234 and 3614 are just in rework. The drafts are not available to industry.

<u>Requirements on equipment</u>

The relevant requirements on equipment are partly covered in the EMC equipment requirements (STANAG 3516 for aircraft, STANAGs 4435 and 4436 for surface ships) in the test “Susceptibility to Radiated Fields”by definition of increased limits. – Requirements on EEDs might be included in STANAG 4238, which is not available to industry.

<u>Requirements on systems</u>

Design requirements covering HIRF for weapon systems equipped with EEDs will be probably included in STANAG 4238, which is a draft and is not available to industry.

<u>System test procedures</u>

System testing is described for weapon systems in STANAG 4324, which also is in rework and not available for industry. – A special document is in planning status for military aircraft, which will probably also cover HIRF (STANAG 7116).

Maintenance and modifications :
A document is also planned to cover generally EM maintenance and maybe also modification aspects, which will probably handle the HIRF problem, too. It is STANAG 7130.

MIL-STDs
Environment :
MIL-STD-464 defines different EM environments for military aircraft operating on ships, for surface ships, space and launch vehicles, ground systems and all other applications. The hardest is the environment on ships. All others are significantly lower.
MIL-STD-464 includes also data about the internal environment on ships (surface metallic/non-metallic, submarine)
Requirements on equipment
MIL-STD-1512 covers the HIRF problem on equipment level for weapon systems equipped with EEDs.
MIL-STD 461/462 takes care of HIRF for equipment for almost all military systems by increased levels for the radiation susceptibility test and also the "Bulk Current Injection"-test
Requirements on systems
The MIL-STD-1310G may also be applied for ships to get some improvement similar like the MIL-STD-1542B for space and launch vehicles. Both standards, however, are not created for HIRF protection.
System test procedures
Nothing is available on MIL-STDs side, how sufficient hardening shall be demonstrated.
Maintenance and modifications
Nothing is also available, how HIRF maintenance and HIRF relevant modifications shall be handled. Information about these subjects might, however, be included in different handbooks.

Commercial Aircraft Documents
A lot of work has been done in the last years from the US (SAE AE4R) and the European specialists (EUROCAE WG 33) to create environment data and test procedures for commercial aircraft. This work has almost be finished. The results are applied in the certification process for all modern commercial aircraft already now.
Environment :
The "Certification Document" defines environments for fixed wing aircraft and helicopters. To save money in design and testing, different environments have been defined, one for critical functions, a significantly lower one for the essential functions. No special HIRF requirement is laid on all other functions (requirement only with respect to Intra-System EMC).
Requirements on equipment
The special HIRF requirements on equipment can be found in the RTCA/DO 160 document in section 20. HIRF is considered with respect to increased test levels for radiated susceptibility tests and for the "Bulk Current Injection"-test, too.
Requirements on system
No special design requirements are defined in the new commercial aircraft documents.
System test procedures
The "Certification Document" defines test procedures for demonstration of sufficient hardening in the whole frequency band from 10 kHz up to 40 GHz.
Maintenance and modifications
The document has recognized the great significance of maintenance with respect to HIRF . It includes some general rules how to proceed.

Other Commercial Standards/Specifications
Standards for commercial equipment do not include a special HIRF requirement for systems up to now. The equipment will be hardened, however, at least up to levels required in the equipment standards (living area : 3 V/m; industrial area : 10 V/m; higher levels possible).

	Environment	Requirements on Equipment	Design Requirem. on System	System Test Procedures	Maintenance	Modifications
General	STANAG 1307 (restricted)	MIL-STD-461D MIL-STD-462D			((STANAG 7130))?	((STANAG 7130))?
Munition, Weapon Systems incl. EED‘s	STANAG 4234* MIL-STD-464	(STANAG 4238) MIL-STD-1512 (EED‘s)	(STANAG 4238) MIL-STD-1385B (repl. by MIL 464)	STANAG 4324*		
Military Aircraft	STANAG 3614* (example) MIL-STD-464 (ship operat.)	STANAG 3516* MIL-STD-461D MIL-STD-462D		((STANAG 7116))		
Ships, Surface, Metallic	MIL-STD-464 (outside + within)	STANAG 4435* MIL-STD-461D MIL-STD-462D MIL-STD-464	MIL-STD-1310G			
Ships, Surface, Non-metallic	MIL-STD-464 (outside + within)	STANAG 4436* MIL-STD-461D MIL-STD-462D MIL-STD-464				
Submarines	MIL-STD-464 (within)	STANAG 4437* MIL-STD-461D MIL-STD-462D MIL-STD-464				
Space and Launch Vehicles	MIL-STD-464	MIL-STD-461D MIL-STD-462D	MIL-STD-1542B			
Ground Systems	MIL-STD-464	MIL-STD-461D MIL-STD-462D				
Commercial Aircraft	HIRF Certification Document	RTCA/DO-160 Section 20		HIRF Certification Document	(HIRF Certification Document)	(HIRF Certification Document)
Commercial Systems						

STANAG xxxx : Available to industry as latest edition

(STANAG xxxx) : Not available to industry

STANAG xxxx* : Available to industry not as latest edition

((STANAG xxxx)) : Planning status

? not known if subject is included

Table 3.-2 : Standards/Specifications covering HIRF

Lightning Protection

General

Lightning has become a great risk for modern systems equipped with electrical and electronic equipment, too. This is especially the case for modern aircraft.

A lot of activities took therefore place between US specialists (SAE AE4L) and European ones (EUROCAE WG 31) to discuss new requirements and new test methods to ensure lightning protection for modern commercial aircraft. A lot of work has already been performed. Some documents have already been published about environment data, zoning and equipment testing, which already represent the basis for certification today. - The activities are still ongoing.

Many of the knowledge found during these activities can (and will) be taken over for lightning protection of other systems, too (MIL-STD-1795A, responsible for lightning protection of military aircraft, e.g., will be replaced by these documents, when they are finished).

Standards/Specifications Required

Similar to HIRF documents should be available for (fig. 3.-1) :

- The Lightning environment
- Requirements on equipment
- Procedures to demonstrate sufficient protection
- Methods to control Lightning Protection during life-time.

These measures can partly be combined with measures to control Intra-System and the external EM effects

- Handling of modifications

No special requirements without consideration of zoning must exist on system design.

Existing Standards/Specifications

A survey is presented in table 3.-3.

STANAG‘s

Environment :

It is covered by STANAG 4236. The last version available to industry is from March 1993. It includes the Multiple Stroke, but not the Multiple Burst, which has been defined meanwhile.- What has also not been defined is the considerable E-field, which will generally be available before a lightning strike. – A special environment with some slightly increased data is included for munitions.

A new version is in preparation, which will probably cover the latest lightning environment data (“close contact between WG 31 and the author of the new edition”).

Requirements on equipment

Nothing is available at this time for equipment testing and qualification.

The STANAG 4236, which has been published as a first draft (not available for industry), will probably cover this field with respect to applicable test waveforms and limits.

The STANAG 4327 will probably include the test set-up`s and test procedures. – Both documents seem to cover not only munitions and weapon systems including EEDs, but a wider variety of systems. (“close contact of author of both STANAGs to EUROCAE WG 31”).

Requirements on systems

STANAG 3659 is available, which describes some requirements to system mainly for metallic aircraft and mainly with respect to bonding.- STANAG 4238 (existent as 1. Edition, not available to industry) might include some requirements for munitions and weapon systems equipped with EEDs.

System test procedures

No system test procedures exist up to now in the published STANAG versions. They will probably be included in STANAG 4327, which has been prepared as a 1. edition and which is not available to industry (“close contact of author to EUROCAE WG 31”). The main field, they will probably cover, seems to be munitions and weapon system equipped with EEDs, but first discussions with the author indicate, that they will take care of a lot of other systems, too. – It is not clear, if the new document will also cover military aircraft, because this might be included in the planned STANAG 7116.

Maintenance and modifications :

Nothing exists today: It might , however, be covered by the planned STANAG 7130.

MIL-STDs

Environment :

The modern lightning environment is included in MIL-STD-464. It is in line with the latest knowledge also about aircraft threat and describes all current waveforms incl. Multiple Stroke and Multiple Burst as well as the waveforms to protect against electric fields.

The MIL-STD 1757A, applied for aircraft lightning protection for many years, has been cancelled meanwhile. The MIL-STD-1795A, which is still applicable today, will be cancelled as soon as the relevant documents for the commercial (chapter 4.4.3.3.) have been finished and will be replaced by them. The document includes already the Multiple Burst, but in the old version with 24 sets of pulse packages.

Requirements on equipment

Mil STD-1512 defines some requirements on EED circuits on the ground. – Nothing is available for component and equipment testing anymore, the leak, however, is closed by application of the new methods and limits for commercial aircraft.

Requirements on systems

Nothing is directly specified, but a lot of handbooks are available how to protect systems also against lightning. – The MIL-STD-1795 includes some general requirements.

System test procedures

Nothing available, but the methods in preparation for the commercial aircraft will be taken over as a guide.

Maintenance and modifications :

Nothing available. Handbooks, however, might include some material.

Commercial Aircraft Documents

Environment :

It is very well defined in ED 84 / SAE ARP 5412 . It includes the latest knowledge about lightning parameters not only with relation to aircraft.

Requirements on equipment

These are very well defined in RTCA/DO 160, Section 23 for “Lightning Direct Effects” (this means structure components) and in Section 22 for “Lightning Transient Susceptibility” (this means for testing of electric/electronic equipment). – The waveforms applied and the limits will also be included in ED 84 / SAE ARP 5412, which might become the leading document. The test procedures will be included in a lightning testing document, which is already in preparation by the SAE/EUROCAE specialists.

Requirements on systems

Nothing than how to define the lightning threat zones for aircraft is defined as a system requirement. The rules are included in ED 91 / SAE ARP 5414. They are significantly different to what has been defined in the MIL-STDs up to now.

System test procedures

A document is in preparation by the SAE and EUROCAE specialists, which will cover this field completely.

Maintenance and modifications :

These areas might be described in a “User`s Guide”, which is in preparation, too. Some guide is already given for modifications in ED 81 / SAE AE 4L- 87-3 document.

Other Commercial Standards/Specifications

Environment :

Some is available at IEC.

IEC 1024-1-1 handles protection of structure of ground facilities against direct effects (“damage of structure”), IEC 61312-1-2 protection against the indirect effects of equipment installed in the ground facilities. – Three different external threat levels have been assumed in each case, which are slightly different. The number of the action integral, for example, is larger for all 3 levels than to be defined for aircraft up to now (“factor of 5 for the largest threat level”).

Requirements on equipment

The IEC 61 312-4 is available for lightning protection of equipment installed in buildings.

Requirements on systems

IEC 61662 presents guide how to assess the risk of damage , which will be caused by lightning.

IEC 61024-1-1/2 handle lightning protection of buildings.

IEC 61312 describes rules, how to protect equipment installed in buildings against the indirect effects of lightning.

System test procedures

Nothing is available how to demonstrate lightning protection for great systems similar to an aircraft etc.

Maintenance and modifications :

IEC 61024-1-2 gives some guide for maintenance and inspection of lightning protection facilities for buildings.

	Environment	Requirements on Equipment	Design Requirem. on System	System Test Procedures	Maintenance	Modifications
General	STANAG 4236* MIL-STD-464	(STANAG 4327) (4236 new)		(STANAG 4327)	((STANAG 7130))? All systems ?	((STANAG 7130))? All systems?
Munitions, Weapon Systems incl. EED`s	STANAG 4236*	MIL-STD-1512	(STANAG 4238)?			
Military Aircraft	MIL-STD-1795A**		STANAG 3659 MIL-STD-1795A**	((STANAG 7116))?		
Ships, Surface, Metallic						
Ships, Surface, Non-metallic						
Submarine						
Space and Launch Vehicles						
Ground Systems	IEC 61024-1/2	IEC 61312-4	IEC 61312-1/2 IEC 61662		IEC 61024-2	
Commercial Aircraft	ED84/SAE ARP 5412	RTCA/DO-160 Sections 22/23 ED84/SAE ARP 5412 Testing STANDARD	ED91/SAE ARP 5414 (Zoning)	Testing Standard (DRAFT)	User`s Guide ?	ED 81 / SAE AE 4L- 87-3 User`s Guide ?
Commercial Other Systems	IEC 61024-1/2	IEC 61312-4	IEC 61312-1/2 IEC 61663-1		IEC 61024-2	

STANAG xxxx : Available to industry as latest edition
STANAG xxxx* : Available to industry not as latest edition
(STANAG xxxx) : Not available to industry
((STANAG xxxx)) : Planning status
? not known if subject is included

** will be replaced by commercial aircraft documents as soon as available

Table 3.-3 : Standards/Specifications Covering Lightning Protection

Electromagnetic Pulse (EMP)

General

The most likely and critical threat is the Exo-atmospheric EMP, also called HEMP (“High Altitude Electromagnetic Pulse”). Most standards and documents available will therefore be related to this pulse only.

3.4.5.2 Standards/Specifications Required

Like for lightning protection should be available fig.3.-1 :

- The EMP environment
- Requirements on equipment
- Procedures to demonstrate sufficient protection
- Methods to control EMP hardening during life-time.

These measures can partly be combined with measures to control Intra-System EMC and the external EM effects.

- Handling of modifications

No special requirements must generally exist on system design. There can be, however, an exception, which has been realized for EMP. If the design requirements on a system specified and realized very carefully, it is not necessary to know the real detailed threat (method applied in MIL-STD 188-125A for protection of Ground Based C4 Facilities).

Existing Standards/Specifications

A survey is presented in table 3.-4.

STANAG‘s

Environment :

It might be defined in STANAG 4145, which is identical with the AEP-4.

Requirements on equipment

STANAG 4145 will probably include a lot of information

Requirements on systems

Some requirements will probably be described in STANAG 4145.

System test procedures

STANAG 4416 is involved in testing of munitions against the EMP.

Some might also be planned in STANAG 7116 (planning status) for military aircraft.

Maintenance and modifications :

Guide might be presented in STANAG 7130 (planning status)

MIL-STDs

Environment :

The 5ns-rise time NEMP is defined in MIL-STD 464.

More information will probably be found in MIL-STD-2119 (restricted).

Requirements on equipment

A test method and a limit id described in MIL-STD-462.

Requirements on systems

Requirements on system design are included in detail in MIL-STD-188-125A applicable for C4-Ground Systems.

System test procedures

Nothing available. It might be included in Handbooks.

Maintenance and modifications :

Nothing available. It might be included in Handbooks

Commercial Aircraft

Not applicable.

Other Commercial Standards/Specifications

Environment :

Some data might be available in IEC 61000-2-9/10 for radiated and conducted environment.

Requirements on equipment

IEC 61000-4-24 presents information, how to test protection devices.

Requirements on systems

IEC 61000-5-3 handles protection concepts against the EMP.

IEC 61000-5-4/5 specifies protection devices for radiated and conducted disturbances.

	Environment	Requirements on Equipment	Design Requirem. on System	System Test Procedures	Maintenance	Modifications
General	STANAG 4145 ? (AEP 4) MIL-STD-464 MIL-STD-2119 (restricted) IEC 61000-2-9/10	STANAG 4145? (AEP 4) MIL-STD-461D MIL-STD-462D IEC 61000-4-24 (Prot. Devices)	STANAG 4145 ? (AEP 4) IEC 61000-5-3/4/5		((STANAG 7130))? All systems ?	((STANAG 7130))? All systems?
Munitions, Weapon Systems incl. EED`s				STANAG 4416		
Military Aircraft				((STANAG 7116))		
Ships, Surface, Metallic						
Ships, Surface, Non-metallic						
Submarine						
Space and Launch Vehicles						
Ground Systems			MIL-STD-188-125A			
Commercial Aircraft						
Commercial Other Systems						

STANAG xxxx : Available to industry as latest edition
STANAG xxxx* : Available to industry not as latest edition
? not known if subject is included

(STANAG xxxx) : Not available to industry
((STANAG xxxx)) : Planning status

Table 3.-4 : Standards/Specifications Covering the EMP

	Environment	Requirements on Equipment	Design Requirem. on System	System Test Procedures	Maintenance	Modifications
General					((STANAG 7130))? All systems ?	((STANAG 7130))? All systems?
Munitions, Weapon Systems incl. EED`s	STANAG 4235 STANAG 4239 MIL-STD-1512	(STANAG 4490) MIL-STD-1512 (EEDs)	STANAG 4434 (packaging)	STANAG 4239		
Military Aircraft	MIL-STD-464 (some guide)		STANAG 3659 (metallic)	((STANAG 7116))??		
Ships, Surface, Metallic						
Ships, Surface, Non-metallic						
Submarine						
Space and Launch Vehicles						
Ground Systems						
Commercial Aircraft						
Commercial Other Systems	EN 61000-4-2	EN 61000-4-2 IEC 61340-5-1/2 (devices)	IEC 61087 (charged surfaces) IEC 61340-4-1 (floor covering)			

STANAG xxxx : Available to industry as latest edition (STANAG xxxx) : Not available to industry
STANAG xxxx* : Available to industry not as latest edition ((STANAG xxxx)) : Planning status
? not known if subject is included

Table 3.-5 : Standards/Specifications Covering E-Static

E- and P-Static

General

Electrostatic effects might cause a lot of problems with respect to performance degradation or damage of electronic components, ordnance hazards, fuel ignition, system interference (e.g. generation of noise into antenna systems) and personnel shocks.

In most cases the Intra-System E-Static problems of a system are solved by design requirements with respect to avoid generation of charge (e.g. conductive paints), earthing and bonding measures to distribute the generated charge and in the case of aircraft by installing special discharge components to reduce the charge on the system.

The main problems, which have generally to be considered, are the cases, where electronic components or equipment and EDDs or weapon system equipped with EEDs will come in contact with other charged up systems or personnel.

Standards/Specifications Required

- Some E-static threat data, which can be expected
- Requirements on equipment/components, where E-Static might be a risk
- Procedures to demonstrate sufficient protection
- Methods to control protection during life-time.

These measures can partly be combined with measures to control all other EM effects.

- Handling of modifications

Existing Standards/Specifications

A survey is presented in table 3.-5.

STANAG‘s

<u>*Environment*</u> :

STANAG 4235 specifies two environments for weapon systems including EEDs. The first is defined with respect to handling by personnel (25 kV ou of 500 pF across 500 to 5000 Ohms), the second considers transport e.g. in helicopters (300 kV out of 1000 pF across 0 to 1 Ohm).

The same environment is also included in STANAG 4239.

<u>*Requirements on equipment*</u>

STANAG 4490 seem to define requirements on EEDs. The document is a first draft and is not available to industry.

<u>*Requirements on systems*</u>

STANAG 3659 includes some requirements with respect to bonding, which are also applicable to E-Static. Only metallic aircraft are considered.

STANAG 4434 specifies requirements for packing of equipment/systems susceptible to E-Static.

<u>*System test procedures*</u>

STANAG 4239 describes good methods, how to test weapons.

The STANAG 7116 in preparation for aircraft might also include something about E-Static (unlikely).

<u>*Maintenance and modifications*</u> :

Guide might be presented in STANAG 7130 (planning status)

MIL-STDs

<u>*Environment*</u> :

MIL-STD-1512 includes an environment on EEDs. (25 KV out of 500 pF across 5000 Ohms) in the version from 1972).

<u>*Requirements on equipment*</u>

MIL-STD-1512 for EEDs only.

<u>*Requirements on systems*</u>

Some guide is presented in MIL-STD-464 which charges might be built up in aircraft.

<u>*System test procedures*</u>

Nothing available. It might be included in Handbooks.

Maintenance and modifications :
Nothing available. It might be included in Handbooks
Commercial Aircraft
No requirement or test has been defined for commercial aircraft electronic equipment in the RTCA/DO 160.
Other Commercial Standards/Specifications
Environment :
EN 61000-4-2 defines as an environment for ESD testing 4-8 kV out of 150 pF across 330 Ohms.
Requirements on equipment
EN 61000-4-2 has to be applied.
IEC 61340-5-1/2 are involved in protection of electronic devices.
Requirements on systems
IEC 61087 is a guide to evaluate discharges from charged surfaces.
IEC 61340-4-1 handles behaviour of floor coverings.
System testing:, Maintenance and Modifications :
Nothing available.

High Power Microwaves (HPM)
Nothing has been specified up to now with respect to HPM.

References
STANAGS (Status : August 1998)

1. STANAG 1307:Maximum NATO Naval Operational EM Environment. Produced by Radio and Radar Edition 2, 4th Febr. 1997

2. STANAG 3516:Electromagnetic Interference and Test Methods for Aircraft. Electrical and Electronic Equipment. Edition 3, 10th May 1993. Edition 4, 2.DRAFT in preparation. Latest edition not available to industry!

3. STANAG 3614:Electromagnetic Compatibility of Aircraft Systems" Edition 3, 8th June 1989 Edition 4, 1.DRAFT in preparation. Latest edition not available to industry!

4. STANAG 3659:Electrical Bonding Requirements for Metallic Aircraft Systems. Edition3, 20th Nov. 1998

5. STANAG 4145:Nuclear Survivability Criteria for Armed Forces Material and Installations (identical with AEP-4)

6. STANAG 4234:Electromagnetic Radiation (200 kHz to 40 GHz) Environment Affecting the Design of Materiel for Use by NATO Forces. Edition 1, 7th July 1992. Edition 2, 1. DRAFT in preparation. Latest edition not available to industry!

7. STANAG 4235:Electrostatic Environmental Conditions Affecting the Design of Material for Use by NATO Forces" Edition 1, 29th Jan. 1993. Edition 2, 1. DRAFT in preparation. Latest edition not available to industry!

8. STANAG 4236:Lightning Environmental Conditions Affective the Design of Materiel, for Use by the NATO Forces" Edition 1, 8th March 1993. Edition 2, 1. DRAFT in preparation. Latest edition not available to industry

9. STANAG 4238: Munition Design, Principles, Electromagnetic Environment. Edition 1, 1. DRAFT in preparation.. Not available to industry

10. STANAG 4239:Electrostatic Discharge Munitions Test Procedures. Edition 1, 13th Oct.1997

11. STANAG 4324 :Electromagnetic radiation (Radio Frequency) Test Information to Determine the Safety and Suitability for Service of EED's and Associated Electronic Systems in Munitions and Weapon Systems. Edition 1, 25th June1991. Edition 2 , 1. DRAFT in preparation. Latest edition not available to industry

12. STANAG 4327 : Lightning Test Procedures to Determine the Safety and Suitability for Service of EED‘s and Associated Electronic Systems in Munitions and Weapon Systems. Edition 1 , 1. DRAFT in preparation New ! Not available to industry

13. STANAG 4416 : Nuclear EMP Testing of Munitions Containing EED‘s AOP 28

14. STANAG 4434 : NATO Standard Packing for Susceptible to Damage by Electrostatic Discharge Edition1, DRAFT 1 in preparation. New ! Not available to industry

15. STANAG 4435 : Electromagnetic Compatibility Testing Procedure and Requirements for Naval Electrical and Electronic Equipment (Surface Ships, Metallic Hull) Edition 1, 2nd March 1993. Edition 2, 1.DRAFT in preparation. Latest edition not available to industry

16.STANAG 4436 : Electromagnetic Compatibility Testing Procedure and Requirements for Nava Electrical and Electronic Equipment (Surface Ships, Non-metallic Hull) Edition 1, 2nd March 1993. Edition 2, 1.DRAFT in preparation. Latest edition not available to industry

17. STANAG 4437 : Electromagnetic Compatibility Testing Procedure and Requirements for Naval Electrical and Electronic Equipment (Submarines) Edition 1, 29th June 1994. Edition 2, 1.DRAFT in preparation. Latest edition not available to industry

18. STANAG 4490 : Explosives, Electrostatic Discharge Sensitivity Edition1, DRAFT 1 in preparation. New ! Not available to industry

19. STANAG 4567 : Unified Procedures for Electromagnetic Protection. Planned

20. STANAG 7116 : Verification Methodology for Electromagnetic hardness of Aircraft. Planned

21. STANAG 7129 : Electromagnetic Compatibility Operational Awareness Procedures. Planned

22. STANAG 7130 : In-Service Maintenance/ Validation of EM Hardening Measures. Planned

MIL-STDs (Status : August 1999)

1. MIL-STD-461D : Requirements for the Control of Electromagnetic Interference,
Emissions and Susceptibility
11th Jan. 1993

2. MIL-STD-462D : Measurement of Electromagnetic Interference Characteristics
Emissions and Susceptibility
11th Jan. 1993

3. MIL-STD-464 : Electromagnetic Environmental Effects, Requirements for Systems
18th March 1997
Superseding :
MIL-STD 1818A, MIL-E-6051D, MIL-B-5087B,
MIL-STD-1385B

4. MIL-STD-1310G: Shipboard Bonding, Grounding and Other Techniques for EMC
and Safety
28th June 1996

5. MIL-STD-1512 : Electroexplosive Subsystems, Electrically Initiated, Design
Requirements and Test Methods
Note 1

6. MIL-STD-1541A : Electromagnetic Compatibility Requirements for Space Systems
30th Dec. 1987
Will become a Guidance Book

7. MIL-STD-1542B: Electromagnetic Compatibility and Grounding Requirements for Space System Facilities
1st March 1988
Will become a Standard Practice Document

8. MIL-STD-1605 : Procedures for Conducting a Shipboard EMI Survey (Surface Ships)
20th Apr. 1973

9. MIL-STD-1795A: Lightning Protection of Aerospace Vehicles and Hardware
1st Aug 1989
Will be canceled, when the documents mentioned in 7.3 as reference are available
10. MIL-STD-2169 : High Altitude Electromagnetic Pulse

11. MIL-STD-188-125A : High Altitude Electromagnetic Pulse Protection for Ground Based C4 Facilities Performing Critical, Time Urgent Missions”

12. MIL-STD-220A: Method of Insertion Loss Measurement for Radio-Frequency Filters
Canceled
13. MIL-STD-285 : Attenuation Measure for Enclosure EM shielding for Electronic Test Purposes, Method of
Canceled; to be replaced by IEEE 299-1991

Commercial Aircraft Documents:

1. RTCA/DO-160 : Environmental Conditions and Test Procedures for Airborn Equipment
Sections cover Intra-system EMC, HIRF and Lightning :
Section 20 : Radio Frequency Susceptibility (Radiated and Conducted)
Section 22 : Lightning Transient Susceptibility
Section 23 : Lightning Direct Effects
Other sections : Intra-system EMC

2. ED 84 / SAE ARP 5412: Aircraft Lightning Environment and Related Test Waveforms
Sept.1997 ED 84, May 1999 SAE
3. ED 91 / SAE ARP 5414: Aircraft Lightning Zoning
July 1998 ED 84, May 1999 SAE
4. ED ? / SAE ARP ?: Aircraft Lightning Testing
DRAFT

ED 81 / SAE AE4L-87-3-Rev.C: Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning”
May 1996

6. User`s Guide : In preparation

7. ED ? / SAE AE4R ?: Certification of Aircraft Electrical/Electronic Systems for Operation in High Intensity Radiated Fields (HIRF)”

DRAFT

Other Commercial Standards/Specifications :

Of main interest in this case are the EN/ICE/CISPR Standards available.

At least the following documents should be taken in consideration :

3.5.4.1 EMC :

Emissions (conducted and radiated) :

- EN 55011 (or CISPR 11) for ISM equipment
- EN 55013 for broadcast receivers
- EN 55014 for household equipment
- EN 55015 for lighting equipment
- EN 55022 for IT (information technology)

The tests are based are based on the (old) CISPR standards. All include measuring methods and test set-up`s.

For power mains related emissions, the following apply:

- EN 61000-3-2 for harmonics (or IEC 1000-3-2)
- EN 61000-3-3 for flicker

Immunity/Susceptibility Testing :

The following documents should be considered in this context :

- EN 61000-4-2 for ESD
- EN 61000-4-3 for radiated field RF immunity
- EN 61000-4-4 for EFT (electric fast transients or burst)
- EN 61000-4-5 for Surge
- EN 61000-4-6 for conducted RF immunity
- EN 61000-4-8 for power frequency (50 Hz) magnetic field immunity
- EN 61000-4-9 and 10 for pulsed and oscillatory magnetic fields (not used)
- EN 61000-4-11 for voltage dips
- other in preparation, but questioned at the moment if they are relevant in practice.

There are also Product Standards available. They give the typical requirements for an individual, e.g. cars. Measuring methods however (and also some pre-defined levels) are given in the basic standards. - When there is no Product Standards available for a special product, a 'generic standard' can be used as a reference.

There are no standards available for large systems without :

- lifts and elevators: EN 12015 and EN 12016
- agricultural machines and ground moving machines: EN 14982
- automotive directive in Europe 95/54
  (with reference to some international ISO standards)

In some cases, combined with subassembly testing, risk analysis is needed in order to reduce the EMC testing to relevant units. Risk analysis and safety related EMC testing is described in:

- EN 61000-1-2 for EMC and functional safety
- EN 61508 subparts 1-7:functional safety of electronic systems AND software

For cabling (especially data communication), generic and installation standards are expected in the near future:

- EN 50173 and EN 50174
- IEC 11801

Further information can be found for :

- for EN standards of CENELEC: www.cenelec.be
- for international standards of IEC:www.iec.ch

3.5.4.2 Lightning Protection :

- IEC 1024-1 Ed.1 / ENV 61024-1 :
  Protection of structures against lightning - Part 1: General principles

- IEC 61024-1-1 Ed. 1.0 :
  Protection of structures against lightning - Part 1: General principles –
  Section 1: Guide A: Selection of protection levels for lightning protection systems

- IEC 61024-1-2 Ed. 1.0 :
  Protection of structures against lightning - Part 1-2: General principles –
  Guide B - Design, installation, maintenance and inspection of lightning protection systems

- IEC 61312-1 Ed. 1.0 :
  Protection against lightning electromagnetic impulse –
  Part 1: General principles

- IEC 61312-2 TS Ed. 1.0 :
  Protection against lightning electromagnetic impulse (LEMP) - Part 2: Shielding of structures, bonding inside structures and earthing

- IEC 61312-4 TR2 Ed. 1.0
  Protection against lightning electromagnetic impulse - Part 4: Protection of equipment in existing structures

- IEC 61662 TR2 Ed. 1.0 :
  Assessment of the risk of damage due to lightning

  - IEC 61662 Amd.1 TR2 Ed. 1.0
    Amendment No. 1
  - IEC 61663-1 Ed. 1.0 :

  Lightning protection - Telecommunication lines - Part 1: Fibre optic installations

3.5.4.3 Electromagnetic Pulse (EMP) :

- IEC 61000-2-9 Ed. 1.0 :
  Electromagnetic compatibility (EMC) - Part 2: Environment - Section 9: Description of HEMP environment - Radiated disturbance.
  Basic EMC publication

- IEC 61000-2-10 Ed. 1.0 :
  Electromagnetic compatibility (EMC) - Part 2-10: Environment - Description of HEMP environment - Conducted disturbance

- IEC 61000-4-24 Ed. 1.0 :
  Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 24: Test methods for protective devices for HEMP conducted disturbance - Basic EMC Publication

- IEC 61000-5-3 TR Ed. 1.0 :
  HEMP protection Electromagnetic compatibility (EMC) - Part 5-3: Installation and mitigation guidelines concepts
- IEC 61000-5-4 TR2 Ed. 1.0 :
  Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 4: Immunity to HEMP - Specification for protective devices against HEMP radiated disturbance.
  Basic EMC Publication

- IEC 61000-5-5 Ed. 1.0 :

Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 5: Specification of protective devices for HEMP conducted disturbance.

Basic EMC Publication

3.5.4.4 Electro-Statics :

- IEC 61087 TR2 Ed. 1.0 :

  Guide for evaluating the discharges from a charged surface

- IEC 61340-4-1 Ed. 1.0 :

  Electrostatics - Part 4: Standard test methods for specific applications –
  Section 1: Electrostatic behaviour of floor coverings and installed floors

- IEC 61340-5-1 TR2 Ed. 1.0 :

  Electrostatics - Part 5-1: Protection of electronic devices from electrostatic phenomena General requirements

- IEC 61340-5-2 TS Ed. 1.0 :

  Electrostatics - Part 5-2: Protection of electronic devices from electrostatic phenomena User guide

4. EVALUATION OF STANDARDS AND PROPOSALS FOR IMPROVEMENT

4.1 Criteria for Improvement

The following criteria will be applied looking for improvement of the existing situation :

Reduction of risks which might exist today

Although the different areas are covered by applicable standards/specifications, there might still be a risk, because the documents are not harmonized. Equipment or systems might be qualified to a certain standard, which is no more sufficient today or which require other levels.

Reduction of effort

Hardening of systems against EM effects and demonstration of sufficient protection as well as maintenance activities requires sometimes a lot of effort. As far as possible it is pointed out, where reduction might be achieved without increase of risk.

Requirements by future techniques

The technique applied in the systems is always in progress. If some problems might be expected in next future, it will be pointed out.

4.2 Consideration of the Different Electromagnetic Effects

4.2.1 Intra-System EMC

The existing situation is pointed out in table 3.-1. – Intra-System EMC will be achieved by requirements on equipment side and realization of protection measures on system side. System test procedures have to be applied to demonstrate Intra-System EMC. Maintenance measures are very often necessary to guarantee the EMC. Of interest are modifications, such on equipment or also structure side. They can have a large influence on the EMC-behaviour.

Requirements on equipment

Requirements on equipment are probably laid down in STANAG 4238 for EEDs (first draft in preparation, not available to industry), for military aircraft in STANAG 3516 and for metallic and non-metallic surface ships in STANAGs 4435/4436. The requirements for submarines are included in STANAG 4437. – All these STANAGs are in an update status. The drafts are not available to industry. It is, however, assumed, that they will follow the latest edition of the MIL-STD-461/462.

That means, the most important military systems are covered in this case and the latest status of technique will probably be included soon. – In the case, where requirements are not specified in a STANAG (e.g. for missiles), the MIL-STD-461D/462D might be applied.

There seems not to be any technical risk with respect to the Intra-System EMC based on military specifications.

Requirements on equipment exist also in the commercial area. The RTCA/DO 160 D has to be mentioned for commercial airborne equipment, a lot of EN`s and IEC`s are available for commercial ground equipment.

Reduction of effort :

The following can be mentioned here :

- Reduction of effort for testing :

Radiated susceptibility have to be performed in the military specifications starting at a frequency range of 10 kHz up to max. 40 GHz. There are a lot of problems just in the lower frequency range. To perform this test perfectly, expensive absorbers would be required. The main coupling, however, will take place in the lower frequency range via cabling. In the committees for commercial aircraft it was therefore decided, to apply the current injection test only in the lower frequency range and to start with radiated susceptibility testing at 100 MHz. A lot of money can be saved by this procedure without any increase of a risk.

- Reduction of effort by use of commercial equipment :

Sufficient standards/specifications are available to control EMC-interfaces of commercial equipment. The RTCA/DO 160 D is applicable for commercial airborne equipment, a lot of ENs and IECs for ground equipment. If a comparison of the different documents with the military requirements would be performed, the way might be open to apply a lot of commercial equipment in different military systems.

Future requirements :

It might be necessary to define specifications with respect to “Modular Avionic”. A lot of PCBs (printed circuit boards) offered by different manufacturers will be integrated in one common case. New tests and limits are required to ensure EMC in this case.

Requirements on system

STANAG 4567 is in planning status with unknown list of content.- STANAG 3569 includes some bonding requirements and guidelines, but for metallic aircraft only. Some special MIL-STDs are available for ship, space and launch application.

There are not too many standards/specifications available in this case, but this does not mean any risk.

Development of the system is generally under the responsibility of the system manufacturer. A lot of handbooks etc. are available for his support. Existing specifications, however, should also consider new materials (e.g. CFC for aircraft)

System test procedures

Intra-System EMC protection has to be demonstrated by testing. Interaction tests only are in most cases not sufficient. Safety margins have to be demonstrated for all electrical circuits/functions of interest.

Nothing applicable has been specified up to now with the only exception of coupling into the EED-circuits, where the HIRF test methods might be applied. Test procedures are also not available in the commercial area.

Testing will mainly take place in large test houses, which have a lot of experience. They apply proven methods, which, however, might differ from test house to test house,

Some general rules and procedures should be defined in this case, that the results get comparable and that all the experience available is collected. This should be done for conducted interference as well as for radiated one including antenna to antenna coupling problems.

Maintenance

Safety of systems might be more and more affected by defect EMC protection measures. Maintenance has to be performed. STANAG 7130 is in an planning status, which will probably cover this area.

Modifications

Change or repair of structure, installation of additional equipment or cabling might have a large influence to EMC protection. A lot of money might be involved, if all the expensive system tests have to be repeated. Rules and methods shall be defined – based on the experience available- how to proceed (e.g. including increased application of computer programs). – These methods could also be included in STANAG 7130 (in planning status).

4.2.2 High Intensity Radiated Fields (HIRF)

The situation is also presented in table 3.-2.

Environment

The latest environment defined by STANAG is included in the 1307. It presents the highest levels produced by radio and radar, which might ever been found in NATO Naval Operations. It is an extremely high worst case environment, which considers average as well as peak levels. It is a very modern environment, which will probably include the latest status of transmitter development and transmitter installation. It is not absolutely clear, where this environment will be applied to, but it is very likely, that weapon systems including EEDs will be considered. - Another environment to be applied for weapon systems equipped with EEDs is defined in STANAG 4234. It is significantly smaller, but it will probably updated in the version, which is in preparation (not available for industry).

A modern environment for weapon systems including EEDs and naval applications is also defined in MIL-STD-464. This environment, however, is significantly smaller than this of the STANAG 1307. – MIL-STD-464 includes also data about (different) environments for military naval aircraft, space and launch vehicle systems, ground systems and other applications. The last one will probably include airforce aircraft.

Different environments are available for certification of commercial aircraft and helicopters.

Reduction of risks :

Safety of modern systems can directly depend on the HIRF environment requirements. There are, however, several different requirements for similar applications, which differ very much. An analysis should be performed about the reasons for these differences.

Many systems, which are still in use, are hardened on the basis of the older electromagnetic environments, for example missiles, etc. These environments have been significantly lower and have often considered only average levels and not the extremely higher peak levels. If the environment has increased like pointed out in STANAG 1307, there should be a potential risk to different systems. An analysis should be performed about the systems which are affected and the transmitters, which are the drivers for increase of the environment to identify the potential risks. – There is probably not a direct risk for the EED-circuits, because sufficient safety margin should be available, but there can be a high risk for the electronic involved, especially to those susceptible to peak levels (e.g. computers).

Reduction of effort :

Hardening against the very high HIRF levels and demonstration of sufficient protection is very expensive. Up to now only one worst case environment is defined by STANAG 1307, which will probably be mainly applied for weapon systems equipped with EEDs.

Other environments like already started in MIL-STD-464, however, are necessary, too.

The levels should be tailored to the systems affected.

To reduce effort significantly without any reduction of safety, the environments can also split up similar to what has done for commercial aircraft. A high environment has been defined, which will guarantee safety and which will only be applied to the safety critical functions. Lower environments will be taken as a basis for essential functions, that means there is a risk of occasional interference.

Requirements on equipment

Special HIRF requirements on equipment are generally included in the EMC standards/specifications applied for achieving “Intra-System EMC”.

There are two special tests to represent also the HIRF requirements, the bulk current injection test and the radiated susceptibility test. In both cases the HIRF requirements will be covered by increased limits.

Relevant requirements are laid down in the MIL-STD-461D/462D and probably also in the STANAG 3516 after the next edition. It is not known, which requirements are on equipment of ships in this case.

Reduction of risk :

Although the MIL-STD-461D/462D is a very new edition, there is a large conflict between the requirements on equipment and the environment requirements laid down in the STANAG 1307 and also in the MIL-STD-464. – The levels, required for example for external stores of aircraft are only 200 V/m, while the requirements of the environment is up to 1270 V/m average and 6680 V/m peak. A similar situation can be found for equipment mounted on the surface of ships.

It seems to be necessary to tailor the equipment requirements more to the environment requirements, especially in these cases, where protection on system levels can not be realized (e.g. equipment mounted in cockpit areas of aircraft).

Reduction of effort :

What has already been mentioned in the relevant chapter of Intra-System EMC is, that the test with respect to radiated susceptibility can be started at 100 MHz instead of 10 kHz.

Generation just of the very high HIRF fields is extremely expensive because powerful generators are required. New techniques should be considered, which allow generation of high fields with not too much effort. Of interest in this case is the “Mode Stirring Camber”, which is already recommended for qualification of commercial aircraft equipment. – There might be some limitations for equipment with a long reaction time. This, however, is just under investigation.

Requirements on system

The STANAG 4238 is in preparation for weapon systems equipped with EEDs. Some requirements are also included in MIL-STD-1385B, which has been replaced meanwhile by MIL-STD-464. – In principle the same is applicable like already mentioned for Intra-System EMC. Responsible is the system manufacturer, his interface to the purchaser is the demonstration of sufficient hardening.

System test procedures

System testing is absolutely necessary. – To produce the extreme high field strength levels as far fields across the whole frequency range in very small frequency intervals, however, requires extreme effort. In general substitution methods will be applied with transfer function and re-injection techniques.

In practice the situation is similar to the Intra-System EMC. The tests will be performed by test houses, which have some experience available. The methods and means applied, however, differ, too.

It seems necessary in this case, to define agreed test procedures, too. A very helpful basis are the substitution procedures defined in the HIRF Certification Document for commercial aircraft. The methods included in this document, cannot only be applied to aircraft.
Some effort can be solved, for example for aircraft, if the tests are coordinated with lightning tests. The test set-up for clearance in the lower frequency range is, for example, the same like for lightning current injection.

Maintenance
STANAG 7130 (in preparation) will probably cover this problem. The same is applicable like for Intra-System EMC. Care should be taken about the fact, that this problem is also in discussion for the commercial aircraft for HIRF and Lightning Protection.- Some more guide might be included in the “User`s Guide” in preparation for lightning protection.
Modifications
The same is applicable like for Intra-System EMC. Some first rules are defined in the HIRF Certification Document. – This problem should also be covered by STANAG 7130.

4.2.3 Lightning Protection

The situation with respect to lightning protection can be taken out of table 3-3.
Environment
The lightning environment is covered in STANAG 4236. The latest edition does not cover the full lightning threat in accordance with the knowledge of today. The Multiple Burst and the E-field threat, for example, is not included. – The document, however, is in the status of rework. The author is member of the relevant EUROCAE committee, that means the next edition will probably cover the complete lightning environment like defined today for aircraft.
MIL-STD-464 already includes the full threat. It has been taken over from the commercial aircraft documents ED84/SAE ARP 5412.
Good environment data for ground stations can be found in IEC 61024-1/2.
Reduction of risk :
Some aircraft accidents, which have happened in the last years, gave indications, that the action integral and the charge of the lightning threat like defined for aircraft today, should be increased.
This is partly already proposed in the new edition of STANAG 4236. The threat levels defined, however, are still below the levels of IEC for ground facilities.
For systems, which require a very high degree of protection, an additional higher threat should be defined.
Requirements on Equipment
Requirements will probably be included in the STANAGs 4236 and 4327. Both are not available to industry. They seem to cover most systems including weapon systems equipped with EEDs.
Similar techniques will probably applied like defined internationally in the relevant EUROCAE and SAE committees (author member of EUROCAE committee), that means, there shouldn`t be any problem or risk.
MIL-STD-1512 defines some requirements on EEDs installed in circuits on the ground.
Requirements on equipment are also defined for equipment on the ground in IEC 61312-4.
Reduction of effort :
Reduction of effort might be in some cases possible by limitation of requirements to selected functions only (e.g. safety critical ones).
In addition reduction might similar to Intra-System EMC be achieved by application of commercial airborne or ground based equipment.

Requirements on system
STANAG 4238 (in preparation, not available to industry) might also cover lightning protection for munitions and weapon systems including EEDs. - STANAG 3559 defines some requirements, also applicable with respect to lightning protection, but only for metallic aircraft. – The MIL-STD-1795A applicable for aircraft, shall be replaced by commercial aircraft documents as soon as they are available.
The situation is similar to Intra-System EMC and HIRF. The system manufacturer is generally responsible for design. The result will be demonstrated by test.
In spite of this it might be very helpful to consider the relevant IEC documents applicable for protection of ground facilities.
System test procedures
No tests procedures are available up to now on the military side. Some will probably be included in STANAG 4327, the STANAG 7116 for aircraft is in a planning status, which might cover lightning protection, too.

The situation today is, that system tests will be performed by different test houses, sometimes applying different test methods.
The only document, which will be available soon, is the Testing Standard in preparation by SAE/EUROCAE for commercial aircraft.
The main points of this document should be taken over by STANAG 7116, if lightning tests should be covered there.

Maintenance

The same is applicable like for Intra-System EMC and HIRF. Lightning protection of systems might be influenced by corrosion, age, etc. STANAG 7130 is in a planning status.
Some information will probably available in the “User`s Guide” in preparation for commercial aircraft.
IEC 61024-2 handles methods for ground facilities.

Modifications

Modifications on structure, wiring, installation of additional equipment, etc. may change the lightning protection situation, too.
Rules have to be defined, how to proceed without repeating expensive tests after each modification. They might be included in STANAG 7130. Some information about change of electronic etc. can be found in ED 81 / SAE AE 4L-87-3.

4.2.4 Electromagnetic Pulse (EMP)

A summary about the documents available is shown in table 3.-4.

Environment:

The Exo-EMP seems to be defined very well in STANAG 4145 and MIL-STD 2119.
The old 5ns-Puls can be found in MIL-STD-464 and in IEC 61000-2-9/10.

Requirements on equipment

They might be included in STANAG 4145.
They are included in MIL-STD-461D/462D in the test CS 116 (conducted signals) and RS 105 (radiated signals).
IEC specifies some requirements for protection devices.

Reduction of risk :

The limits specified for CS 116 are 5 A (Airforce) respectively 10 A (Army, Navy) only for the maximum levels to be injected. These levels might in many cases be too weak.

Requirement on systems

STANAG 4145 might include some requirements. IEC 61 000-5-3/4/5 defines some rules how to protect commercial systems on ground.
MIL-STD-188-125 A presents design requirements for C4 ground systems.
In principle it is the same situation like for Intra-System EMC, HIRF and Lightning Protection. The system designer is responsible for sufficient hardening, which has generally to be demonstrated by system testing.

System test procedures

Sufficient system hardening will - similar to the other EM effects discussed up to now –generally be demonstrated by test houses with a lot of experience in this field. Nevertheless it seems to be very helpful, if some general test procedures would be described, which include all experience collected up to now.

Maintenance and modifications

The same is applicable like for the other EM effects. STANAG 7130 (in preparation) should probably cover this field, too.

4.2.5 E- and P-Static

Table 3.-5 presents a survey about what is available.

Environment

On the military side environment requirements have only be defined for EEDs respectively weapon systems including these components. Two possible sources of charge are considered, the personnel source and a possible contact to aircraft/helicopters/other systems during transport.

On the commercial side are also requirements on electronic equipment. Only a personnel source is considered, which is, however different (weaker requirement) to the military one.

Requirements on equipment

On the military side are only requirements on EEDs and weapon systems with EEDs. The commercial side handles commercial electronic equipment.

Reduction of risk :

It might be helpful in many cases to have an E-Static test for military electronic equipment, too. It might be of special interest for computers, etc.

Requirements on system

STANAG 4434 defines some requirements on packing of susceptible loads. STANAG 3659 includes some bonding requirements, which will also help to avoid E-Static effects.

IEC 61087 handles charged surfaces, IEC 61340-4-1 floor covering.

System test procedures

STANAG 4239 covers EED/weapon testing, the planned STANAG 7116 might also cover system testing. – Some ideas of charging up a whole aircraft are included in MIL-STD-464.

Maintenance and modifications

Some guide should be included in STANAG 7130 (in planning status).

4.2.6 High Power Microwaves (HPM)

Nothing is officially available now with respect to HPM. Due to the existing future risk, however, some work should be started.

4.3 Summary of Most Important Improvements

A summary of the most important improvements is presented in table 4.-1 for Intra-System EMC and HIRF and in table 4.-2 for Lightning Protection, EMP, E-Static and HPM.

	Definition of Environment	Requirements on Equipment	Requirements on Systems	System Rest Procedures	Maintenance Procedures	Modification Procedures
Intra-System EMC	n.a.	- Test effort for expensive radiated susceptibility tests can be reduced - Commercial equipment might be applied (especially ground systems) - New procedures for Modular Avionic in Future	Existing requirements should also consider new materials	Agreed system test procedures should be available (for a/c in preparation?)	Maintenance procedures shall be available (in preparation)	Modification procedures shall be available (in preparation ?)
HIRF	- Risk analysis required for use of older systems - Analysis and harmonization of different environments required - Environments depending on criticality mmay help to save effort.	- Test effort for expensive radiated susceptibility tests can be reduced - New test methods should be considered - Limits sometimes not in line with new environment requirements	Existing requirements should also consider new materials	Agreed system test procedures should be available (for a/c in preparation?) (for commercial aircraft available)	Maintenance procedures shall be available (in preparation)	Modification procedures shall be available (in preparation ?)

Table 4.-1 : Summary of Most Important Results, Intra-System EMC and HIRF

	Definition of Environment	Requirements on Equipment	Requirements on Systems	System Rest Procedures	Maintenance Procedures	Modification Procedures
Lightning Protection	- Not sufficient now; probably sufficient in next documents - Safety critical applications might require higher levels that defined for a/c today (probably partly realized in new documents	Available for commercial a/c. Will probably be taken over for in new STANAG. (seem not to be foreseen for a/c)	Existing requirements should also consider new materials	Agreed system test procedures should be available Probably included for different systems in new STANAG. (for military a/c in preparation? ; soon available for commercial a/c)	Maintenance procedures shall be available (in preparation)	Modification procedures shall be available (in preparation ?)
EMP	ok	Limits seem sometimes too low		Agreed system test procedures should be available (for military a/c in preparation?)	Maintenance procedures shall be available (in preparation)	Modification procedures shall be available (in preparation ?)
E-Static		Test for equipment should be available ("EN, IEC")			Maintenance procedures shall be available (in preparation)	
HPM	Nothing available	Nothing available	Nothing available	Nothing available	Nothing available	Nothing available

Table 4.-2 : Summary of Most Important Results, Lightning Protection, EMP and E-Stat

5. RISKS IN EMC OF FUTURE SYSTEMS

The integration of equipment into systems from the point of view of designing for EMC can traditionally be considered from a number of points of view:

- Ensuring that a number of equipment, when connected together to provide a system function, will operate as designed without interfering with each other or being susceptible to the electromagnetic environment in which the systems is immersed.
- Ensuring that a number of separate system functions, when co-located, often in close proximity within a vehicle, will operate as designed without interfering with each other or being susceptible to the electromagnetic environment in which the systems is immersed.
- Ensuring that a complete military system (e.g. tank, missile, aircraft or ship) can operate with other systems in the battle space as designed without interfering with each other or being susceptible to the electromagnetic environment in which the systems is immersed.

At all levels of integration there is wide commonality of the considerations to be taken when designing for EMC, these include:

At the level of the platform operating in the battlefield:

- The electromagnetic emissions (intentional and unintentional) produced by the complete system and their impact on the battlefield in which they will operate co-operatively with other complex systems and the susceptibility of the complete system to the electromagnetic environment of the battle space (including both natural and man-made environments).

At level of the complete weapon system:

- The electrical design of the containing shell (e.g. rack, vehicle chassis, airframe etc.) in terms of bonding, material usage and topology in order to create a desired internal, electromagnetic environment in which the sensitive electronics are contained, when the platform is immersed in an external environment.
- System architecture in terms of signalling level and type versus cable length and environment and the design of cable systems in terms of formats (e.g. twisted or coax), shielding, termination (particularly of the shields) and routing to complement that systems architecture.

At the level of the equipment which contains the sensitive electronics:

- The design of the interface circuitry (e.g. filtering and format) between the sensitive electronics and the interconnections to the rest of the system and the electromagnetic design of the containment system.
- The design of the printed circuit boards (PCBs), which provide the inter-connections between the components, to ensure freedom from internal interference for all operating modes of the equipment.

Although the varieties of considerations have been quoted separately there are balances to be struck between all considerations and it can be seen that EMC is a significant integration concern for complex systems.

5.1. Risk Analysis.

It is anticipated that the risks in designing for EMC will increase unless research & development (R&D) is carried out to address these risks. Risks will arise in a number of ways, namely:

- Increases in existing known risks as a result of tighter commercial pressures arising from competition.

- Technological change.
- Tighter requirements from customers.

It is well understood that unless investment in R&D is made risks will increase, even in the absence of new technology or requirements, because of the continually changing world. This part of the report considers the likely risks that must be addressed and a mitigation strategy is proposed.

First of all a list of risks must be created and then each risk must be examined in more detail to determine the impact, the likelihood of occurrence and a possible mitigation strategy. It is worth dividing the risks into one of three groups depending on the cause as outlined above.

5.1.1. Commercially driven risk

(a) The true electromagnetic behaviour can only be judged when the complete system under consideration is assembled. This only occurs very late in the programme, making modification in the event of design failure very expensive. Fixed price procurement makes late discovery of problems totally unacceptable.

(b) The high power facilities required to demonstrate ultimate performance are a rare resource and are required to be reserved well in advance and that date MUST be kept. This is a considerable risk in a long complex programme. The various test establishments presently available in the Western World, usually financed by National Governments are being closed or “privatised”. This will ultimately result in significant competition for time in the remaining facilities. Such time will become “fixed points” in the programme.

(c) There is considerable pressure to use “commercial-off-the-shelf” (COTS) equipment in military systems. This equipment is unlikely to have qualification evidence or even be designed to meet the military electromagnetic environment as required at present. This becomes of even greater concern in the case of increased requirements in the environment of the future (e.g. Directed Energy Weapons (DEW)).

5.1.2. Technologically driven risk

(d) There is a growing trend in military and commercial systems for the level of integration to be taken to a more fundamental level (e.g. integrated modular avionics (IMA) in the aircraft business). In such cases circuit boards or modules at least will be required to operate in close proximity within a rack or frame and be capable of being relocated or changed regularly through service life without re-testing. In this case the definition of an “equipment” has changed. Furthermore the electrical and mechanical interface between these new equipment and the systems into which they are to be integrated has also changed.

(e) In all weapon systems, the use of using electromechanical power instead of hydraulics or mechanical power is increasing. This places very high current conductors in close proximity to low current/voltage critical signal cables. This increases the risks associated with systems integration from an EMC point of view.

(f) A lack of precision in the definition of the external (see Section 5) and internal environment in which the system is immersed inside the vehicle leads to sub-optimal protection design. In some ways it is impossible to provide a precise definition, however, a lack of knowledge about the statistics of the environment experienced in service life, leads to the environment being defined in a deterministic way. It may be more appropriate for the environment to be defined in a stochastic manner (c.f. reliability). The EMC performance would then be quoted in a similar manner.

(g) The disparity between the results obtained from tests on part of the system in the qualification laboratory and the results achieved when the entire system is integrated is an issue that if improved would bring enormous qualification benefits.

(h) There is a lack of detailed knowledge about the out-of-band behaviour of the components that comprise the system and particularly the equipment. This increases the risk of equipment and system design for EMC. Although proven modelling tools for PCB design have yet to emerge, with or without component behavioural models.

(i) The growing use of electrically complex materials in the structures of platforms makes the integration of the systems within the structure more difficult. Furthermore, ensuring the correct electromagnetic performance of the structure becomes a strongly multi-disciplinary design issue.

(j) There will be considerable design conflict in the future associated with meeting the requirements for antenna installed performance and other performance constraints such as low observability.

(k) There is a trend towards the use of conformal or suppressed antennas. These involve considerable installed performance modelling challenges

5.1.3. Customer Requirement Driven Risks.

(l) As the external environment requirements become harsher the costs associated with the qualification of the whole system rise dramatically. New qualification techniques, which avoid the enormous power requirements and therefore the costs, must be examined.

(m) At present the weapon systems are qualified on a type approval basis just prior to entry into service. There is no attempt to check the continued EMC performance during service life. This situation cannot continue and the customer will demand either guarantee (which may be impossible to give) or some form of maintenance and assurance programme for the continued EMC performance. This is a new challenge to EMC engineers.

(n) The potential for economically producing malicious electromagnetic threats is growing. The customer is likely in future to include such threats in the requirements and these will focus attention on EMC performance because the probability of intercept with such threats must be considered to be unity. Present EMC requirements, although not quoted, are known to have a low probability of intercept.

5.2 Specific considerations for safety related systems

Applying the EMC Directive to large systems can cause a lot of problems in practice, especially for large industrial machines. The new guidance document on the application of the EMC Directive is suggesting some ideas for solving this problems, but gives no practical procedure to be followed. Because a lot of manufacturers of large industrial machinery recognized these problems from the early stage for complying with the EMC Directive, an 'ad hoc' task force within their professional association in Belgium has worked out a procedure for applying the EMC Directive in practice for large systems. This procedure will be presented and discussed in this paper.

This procedure applies to large industrial machines, which can be characterised by the fact that it causes a problem to perform EMC testing under normal laboratory conditions, due to large weight , big size, transportation problems and access to a laboratory, time needed to build-up the machine, ...

Testing of the whole machine, as well as of the separate units called Electronic Sub-Assemblies (ESA) are considered within this procedure, which is mainly based on the limits and requirements set by the generic standards on EMC, but refers also to the EMC requirements set by the Machine Directive.

Introduction. - The procedure which is discussed in this paper, has been worked out in order to be applied as a means to achieve the conformity with the essential requirements of the European EMC Directive (89/336) and the EMC requirements of the European Machine Directive (89/392).

The procedure applies to the electromagnetic compatibility of large, industrial machines, which can be characterised by the fact that it causes a problem to perform EMC testing under normal laboratory conditions. This can be due to:
* large weight
* big size and dimensions
* transportation problems and access to a laboratory
* time needed to build-up the machine
* power consumption
* auxiliary equipment and installations needed
* other ...

Electrical/electronic sub-assemblies or ESA's (as separate technical units) intended for fitment in these machines are also within the scope ot this procedure. This allows a very easy handling of extra tools and options, when added to the standard machine.
The procedure describes the requirements on EMC (European Directive 89/336 on EMC) and the related safety requirements (European Directive 89/392 on Machines), and the procedures necessary for testing. The following disturbance phenomena are dealt with:
* electromagnetic interference by emission
* eletromagnetic field immunity
* current injecting immunity
* LF-magnetic field immunity (if applicable)
* electrostatic discharge (ESD)
* conducted transients
* voltage fluctuations, dips and interruptions
* harmonics and flicker

In the next sections, requirements and testing methods will be discussed in more detail.

Requirements.

General requirements.

It is important to mention here that a product is covered by the Directives, if it is in the field of application and presents potential hazrads with respect to EMC. This means that it should be contemplated in one or more essential safety and/or protection requirements, and for which a protective action is justified. This is an exclusive manufacturers decision. The manufacturer is the only and ultimate responsible for the conformity of this product to the directive. Furthermore, he is the only one able to evaluate the hazards that the product may or will present when used as intended. He will do such evaluation by the way of a hazard analysis or risk analysis, that, once done, will allow him to decide which specific parts of the machine or ESA's should be tested and for which specific requirements, and at which level of severity.

Fulfillment of the requirements.

The requirements of this procedure are deemed to be fulfilled, when:
* the complete machine fulfills the general requirements. In this case, no routine tests of the ESA's are requested.
* all ESA's are fulfilling their specific requirements, and when they are properly installed, in conformance with their recommended installation procedures.
* the machine has no such equipment for which an interference or immunity test is required.

Testing.

It is chosen for a kind of "type testing" as test procedure. Due to this choice, tightened limit values apply for the radiating tests, in order to account for insignificant differences between the test specimen and the series product, and for the repeatiblity and reproducibility of the test rresults themselves.
This choice means also that the reference limits are taken as a basis for a hundred percent testing of the production and for inspection.

If the machine is part of a larger system, or can be connected to auxiliary apparatus, then the machine will be tested while connected to the minimum representative configuration.

Specific rules for Immunity testing.
Referring to the hazard or risk analysis, no disturbances shall occur during the testing which may affect the safety of the machine: it concerns movements of parts of the machine and modifications on the state of function which may generate hazards or mislead others. For this functions, performance criterium A must be achieved, as this criterium is defined in the generic EMC standards for immunity testing (EN 50082-1/2).
For the other essential functions of the machine, they should comply with the performance rrequirements as set by the manufacturer.

All tests shall be performed in the most susceptible operating mode in the frequency bands being investigated consistent with normal applications. The configuration of the test sample shall be varied to achieve the maximum susceptibility (Worst Case Configuration), following the results from the hazard or risk analysis.

It may be determined from considerations of the hazard analysis and/or of the electrical characteristics and usage of a particular machine or ESA that some of the measurements or tests are inappropriate and therefor unnecessary. In such case, it will be required that the decision no to test is recorded in the test report.

Emission measurements.
At the level of the machine, the measurements are performed 'in situ'. Referring to ongoing EN proposals and amendments, no groundplane should be applied.

In order to reduce the test-time, the following method is used for continuous noise:
- first, a measurement is performed using PD. If the measured values are lower than the QPD limits, the machine will comply.
- if the PD measured values are exceeding the QPD limits, a QPD measurement is peformed only at these frequencies.

conducted emission.
For conducted emission testing, a LISN should be used complying with EN 55011 requirements. In case of a 3-phase main power system, the method is also applicable phase per phase. In order to avoid dammage of the LISN from the in-rush currents of the machine, a special shunt-circuit can be used. In cases of high current, a 1500/50 Ohm probe (as referred in EN 55011) may be used, either in a single phase/three phase version.
When it is impossible to perform voltage disturbance measurements, the common mode currents of the main power supply can be measured, using appropriate current clamps or current probes.

The procedure provides limits for both disturbance voltages or disturbance common mode current, in function of the mains input current. Three levels of limits are given, based on a division of the input current as:

- lower than 25 A
- between 25 A and 100 A
- over 100 A

The limits are based on other proposed EN standards. The rationale for the different limit levels is due to the fact that in industrial environments, machines which have a high current or power consumption, will also be connected onto an own transformer station. In this way, higher conducted interference levels can be allowed, as long as the own plant is not disturbed.

radiated emission.
For radiated emission testing, limit levels are provided for 3 measuring distances, namely 30m, 10m and 3m. It is evident that for in situ measurements, 30m measuring distance cannot be used, because or normal rather high background levels. Preferably, the ambient noise shculd be at least 6 dB less than the radiated noise of the machine under test.

Therefor, an appropriate procedure should be applied for discrimination between ambient noise and radiated emission by the machine under test. The method used herefor and its rationale must be reported in the test report.
As an example, a method is reported, where the machine under test is switched on/switched off, so that at the specific frequencies to be controlled, a momentaneous discrimination between machine and ambient noise can be performed.
In case there are no other possibilities, a measuring distance as close as to 1m is acceptable, using a correction factor of 20 log(Ds/Dm). For this method, it is referred to a French Telecom Standard (ref. 112-30), where a measuring distance of 1m is used for in situ measurements of telecom equipment at the customer premisses.

At least 4 measuring points around the machine must be tested. The position of the test points, and also the exact number of measuring points, are defined by the former hazard analysis. At least one antenna height of 1.5m is used. Other (fixed) antenna heights may be used, depending again from the former hazard analysis, showing the locations with the highest emission levels.

specifications concerning ESA's.
If the way of ESA testing is used, the specific harmonised European standards must be applied for the type of ESA under consideration. Examples are the specific European standards for PLC's (programmable controlllers) and for frequency convertors. If no specific standard is available, the above method and procedure should be used.

Harmonics and flicker.
For harmonics and flicker, it is referred to the EN61000-3 series of standards and proposed standards.

Immunity testing.
At the level of the machine, the tests are performed 'in situ', when technical possible and performed in such way, that there is no risk for other apparatus, equipment or installations.

For functions concerning the safety of the machine, the performance criteria A as set in this procedure must be considered as minimum recommended requirements. They can be more severe, depending on the outcome of the hazard analysis.
For the functions of the machine, the mentioned requirements must be considered as normal recommended requirements.

ESD.
For ESD, the safety requirements are set a 15 kV air discharge severity level with a performance criterium A, where for the normal functions only 8 kV with a criterium B is required.

Radiated immunity.
10 V/m field strength is required for all cases.
A uniform field distribution is not required: an uniform field can not always be achieved for these types of large machines. Following the outcome of the hazard or risk analysis, the field strength must be obtained at the location of the specific part under test.
25 % field strength is added for type testing.

EFT.
Depending on both safety functions and process control functions of I/O, signal and control lines, both severity levels and performance criteria are different.
Possible injection methods can be single phase, and using a capacitive clamp (or equivalent capacitor) even for the main power supply.
The reason is that in many cases, the coupling networks cannot hold the large currents of the machine, or even that the installation of the machine does not allow to disconnect the main power supply lines, in order to couple them through the EFT coupling network.

When technically impossible to perform any form of this test on the machine level, the critical ESA's must comply with the requested requirements.

Surge.
Depending on both safety functions and process control functions of I/O, signal and control lines, both severity levels and performance criteria are different.
Possible injection methods can be single phase, or another equivalent coupling mechanism.
Because surge is simulating an overvoltage on the lines due to external transients, the hazard or risk analysis should indicate on which lines a surge test must be performed, if technically possible. Otherwise, the critical ESA' must comply the requested requirements.
External protection devices, which are required in the installation manual, must be included in the test setup.

Injected current.
The injected current can be applied using coupling networks (CDNs). But due to practical problems, especially for the main power supply lines, the use of a current injection clamp is accepted.
When technically not possible, the critical ESA's must comply with the requested rrequirements.

Voltage fluctuations, dips & interruptions.
Depending on safety functions or other functions of the machine, the performance criteria required will differ for the different types of voltage fluctuations, dips and interruptions.
It should also be mentioned again that on the machine level, these tests cannot always be performed, because of the high current level and/or the impossibility to disconnect the main power lines, in order to pass them through the test equipment.
Therefor, the critical ESA's must comply with the requirements set for the machine.

Power frequency magnetic fields.
If this test is applicable, ie. when there are magnetic sensitive devices used, a power frequency magnetic field must be generated at the level of these devices.
When no global test can be performed, or the critical ESA's must comply with the requested requirements.
Another possibility is to use small coils to test locally the different magnetic sensitive devices in the machines. Small coils are described in the standard EN 55103-2 (EMC for professional audio, video and entertainment apparatus).

specifications concerning ESA's.
If the way of ESA testing is used, the specific harmonised European standards must be applied for the type of ESA under consideration. Examples are the specific European standards for PLC's (programmable controlllers) and for frequency convertors. If no specific standard is available, the above method and procedure should be used.

5.3. Proposals for Risk Reduction.

RISK	Impact	Likelihood	MITIGATION
Commercially Driven Risk			
(a) Late risk exposure in a fixed price environment.	HIGH	MED	Improve the capability of modelling and the relevance of equipment test techniques
(b) Reducing number of specialist facilities for whole system clearance	HIGH	MED	Reduce reliance on specialist high power facilities by whole system test technique development
(c) The introduction of COTS equipment into a system with harsh EMC requirements.	MED	HIGH	Improved commercial specifications and greater design influence in systems installation.
Technologically Driven Risk			
(d) Electromagnetic Integration of IMA	HIGH	HIGH	Develop module qualification test techniques.
(e) Electromagnetic Integration of “more-electric- systems”	MED	MED	Development of cable harness design tools
(f) Stochastic definitions of EMC and installed antenna performance	MED	MED	Develop stochastic viewpoint on all coupling phenomena
(g) Lack of correlation between equipment qualification results & whole system performance	MED	MED	Improve the equipment qualification test techniques.
(h) Out-of-band behaviour of system components and antennas	MED	MED	Improved access to details of components or place contractual requirements on provision of mini-models.
(i) Use of electrically complex materials in structures makes the integration on to and within the structure more complex	HIGH	HIGH	Develop modelling capabilities which can account for complex materials
(j) Conflicts between installed antenna performance and other requirements.	HIGH	HIGH	Development of installed performance models to contribute to multi-disciplinary design.
(k) The increased use of suppressed or conformal antennas.	HIGH	HIGH	As above but with added capability for complex antenna elements.
Requirements Driven Risks			
(l) Test cost escalation with increasing environment levels	HIGH	HIGH	Develop test & qualification techniques which are not heavily reliant on full-threat testing
(m) Meeting the demand for production sample testing and in-service testing	MED	MED	Development of reduced cost surveying techniques
(n) Meeting new threats such as HPM.	MED	MED	As in (l) above.

6. RECOMMENDATIONS

6.1 Recommendations for developments in modelling techniques

- Development of techniques for coupling different codes applicable to different regimes of the complete problem
- Definition of validation criteria for EMC modelling codes
- Development of data capture and CAD cleaning processes
- Development of special elements to cater for advanced materials and small but influential details
- Development of PCB modelling tools
- Development of component models
- Development of antenna element models

6.2 Recommendations for developments in test techniques

- Development of guidelines or standard recommended practices for intra-system EMC, HIRF, lightning, EMP, HPM testing
- Validation of direct current injection techniques and methods using mode-stirred chambers
- Development of integrated test techniques for equipment and systems
- Development of test techniques for in-service and production sample testing for equipment and systems
- Derivation of stochastically based safety margins

6.3 Recommendations for development of standards

- Completion of existing standards
    - System test procedures
    - Maintenance and modifications
- Application of commercial standards for systems
- Commercial aircraft (lightning + EMC)
- Ground facilities (EN + IEC)
- Updating requirements for equipment to new environments
- New standards for HPM
- New standards for modular avionics
- Reorganization of standards (similar to MIL-464 hierarchy)
- Standardization of electronic formats of equipment qualification data for system use
- Harmonization of different standards in order to avoid repetitions

6.3.1 Development in Published Standards

The tables 3.-1 to 3.-5 present a large number of standards/specifications, all handling Intra-System EMC and the most important electromagnetic environment effects. – Further standards have to be added, if also electromagnetic areas would be considered, which have not be included in this report. – The list would be extended again, if all commercial standards and specifications, which are available, would be mentioned, too.

All the military standards/specifications are needed for military system design and to ensure, that sufficient protection is guaranteed during life time of the systems.

Some important data (e.g. the environments) or procedures are called up in different documents. Some documents are based on an older technical standard or status of knowledge, others on newer ones. To avoid conflicts and also risks, a lot of the existing documents need always be updated and harmonized. The intervals should not be too long.

In addition, in spite of all the documents available on the military side, it can be seen, there a still some missing.

Both, to update and harmonize the existing documents and to create new ones, needs a lot of work/effort and a lot of time.

The way out is to create such as a leading document just for the important field of system development, which is based on the greatest number of standards to involve more and more this, what is already available to improve the documents or to fill the leaks. This means mainly the involvement of commercial standards/documents. There are a lot available (see “references”). They have to be analyzed very carefully with respect to their military applicability. In many cases, however, they might be sufficient.

This way has already be gone by MIL-STD-464, although many things might to be improved.

It presents in a very concentrated way for all systems (airborne, sea, ground, space) a survey of the requirements with respect to all electromagnetic requirements, starting e.g. at power line transient level up to EMP protection and TEMPEST. If the requirements are not included in the standard itself, it calls up the applicable documents. These are not only military ones, but also commercial ones!

Several MIL-STD´s have already been replaced by MIL-STD-464, that means the

- MIL-STD-1818A : “Electromagnetic Effects Requirements for Systems”
- MIL-STD-6051D : “Electromagnetic Requirements, Systems”
- MIL-STD-1385 : “Preclusion of Ordenance Hazards in Electromagnetic Fields; General Requirements for”
- MIL-B-5087 B : “Bonding, Electrical and Lightning Protection for Aerospace Systems”

In addition, the MIL-STD-464 includes a lot of guide, how to perform protection in the different areas and which handbooks are available to solve the problems. The actual standard, for example, consists of 16 pages, the appendices with the guide lines of 95 pages.

Commercial standards will directly replace some MIL-STDs, too.

Important examples are :

- MIL-STD 285 : “Attenuation Measure for Enclosures EM shielding for Electronic Test Purposes, Method of”

It is replaced by IEEE 299-1991

- MIL-STD 1757 A: “Lightning Protection for Aerospace Vehicles on Hardware”

It will be replaced by the documents prepared for lightning protection of commercial aircraft as soon as available.

A lot of MIL-STDs have been cancelled without any replacement or by bringing them down to Handbooks or Standard Practice documents, that means, there seems to be something like a cleaning-up”-process.

It might be reasonable, if STANAG would follow similar procedures. A document similar to MIL-STD-464 might already be in a planning status with STANAG 4567.

6.4 Recommendations on legacy systems

- Examination of the impact on operational role of increased environment
- Assessment of critical circuit technology in each system
- Recommendations produced on restrictions

It has been pointed out in chapter 3.4.3 of this report, that a new “High Intensity Radiated Field” environment has been specified by NATO in STANAG 1307. This environment reflects the higher output power of the transmitters installed, their new modulations and the new frequency bands taken more and more in use.

This new environment is significantly higher than all environments specified ever in the past. It specifies also very large amplitude pulse modulated signals, which have been found to be very important for modern digital electronic equipment.

This environment will be the basis for hardening of all future NATO weapon systems to guarantee safety and mission performance under all circumstances.

Under the preposition, that this environment reflects the existing situation, problems can not be excluded for the existing weapon systems which are in use today. They are generally hardened in accordance with older and weaker specifications. Safety might be affected in this case as well as mission performance.

To avoid any future risks the following procedures are proposed :

- Identification of the transmitters and situations responsible for the significant increase of the new environment.
- Performance of an analysis, which weapon systems might be affected by these increased levels. - The basis for a first evaluation should be the assessment of the critical technology installed in the different systems.
- As a result information is available, which constellations between which weapon systems and transmitters installed on carriers or outside will probably be critical. These situations can than be avoided e.g. by restrictions.

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14. Abstract

The study has focussed on three areas of EMC design, development and qualification in future defence systems, namely:

- Numerical modelling
- Test techniques
- Published standards

The limitations of existing techniques and standards have been examined and highlighted. Such limitations cause risks at the present time. However, the risks will increase as a result of changes in the commercial and technological environment and potential increases in risk as a result of these changes in the absence of research development, have been highlighted. Furthermore, recommendations on investment in research and development have been made in order to mitigate the increasing risks.

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Fachinformationszentrum der Bundeswehr, (FIZBw)
Friedrich-Ebert-Allee 34
D-53113 Bonn

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Defence Industry Research & Technology General Directorate
Technological R&D Directorate
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