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Electromagnetic modelling / Modélisation électromagnétique

Foreword

This special issue of the Comptes rendus Physique reports on a one-day scientific meeting at ONERA held in March 2005. This meeting had been dedicated to recent progress made in research in the domain of numerical simulation of electromagnetic wave propagation.

The massive use of numerical analysis and computation in electromagnetism is relatively recent compared to what has happened in mechanical sciences. Although the first discretization scheme of Maxwell's equations (the famous Yee scheme) dates from 1966, the true development of applied mathematics in electromagnetism has begun in the 1980s. Ever since, this branch of science has made spectacular progress and presently we can observe that scientific computation occupies a predominant place in electromagnetic research and development, not only in research laboratories but also in the aeronautics industry, ground transportation and electronic industry. This has involved a formidable effort, considering the very vast field of applications concerned: wave propagation, radar detection, antennas and electromagnetic compatibility, inverse problems in medical applications and geophysical exploration, optics, nano-technology in electronics and optics, …

The progress in the development of numerical methods for Maxwell equations has benefited from the contributions and collaborative efforts of researchers from two scientific communities, electromagnetism and applied mathematics, who learned to ask the same kind of questions. The implication of the first is evident and has been essential in the definition of the right problems, the description of physical phenomena and indicating major problems. They have started many of the now classical techniques for the solution of Maxwell's equations and contributed to their validation on more and more complex problems. The contributions of the second group have shown to be fundamental. Revisiting the problem of EM modeling, they have done what mathematicians are supposed to do, introduce mathematical rigor and abstraction. Thanks to their relations with similar application domains (acoustics, elastodynamics, hydrodynamics, …) they have helped researchers working in specific domains to benefit from the progress made in others.

At the heart of this important stream of scientific research, French research had an important role to play, undoubtedly due to a strong tradition in applied mathematics. The purpose of this Scientific Day in March 2005 was to account for the most recent progress in this realm. We think that this has allowed us to present a significant and representative panorama of the field, without being exhaustive, which would have been difficult because of the sheer size of the scientific community in France (counting both researchers and engineers): think only of the *GDR Ondes* (Wave Research Group), of which the scientific kernel is mostly concerned with electromagnetism, already involving more than 1000 people. For example, the important themes of absorbing boundary conditions, perfectly matched layers, fast multi-pole techniques and high frequency asymptotic modeling have not found the place they merited.

For the organization of this day, we have observed the following guidelines:

– consider equally the fundamental and the applied aspects of research, in particular by putting in the foreground some collaborations between academia and industry;
– present problems both from the time domain perspective, and problems in the time-harmonic regime. This was essential because we know that, although intimately related, these points of view lead to problems of a very different nature, both as to the mathematical analysis as well as to the numerical aspects. They also correspond to

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different domains of applications and their particularities to cope with (wide band analysis, varying directions of illumination);
– handle methods for partial differential equations (finite elements, finite differences, finite volumes, ...) and methods for integral equations (boundary elements, global discretizations) on an equal footing.

We have had eleven contributions, eight of which have been transformed into a written article, included in this issue. These papers treat the following themes:

Domain decomposition methods in the time-harmonic realm

Any time we want to handle a real-size problem, the computational resources needed pose severe problems, particularly for three dimensional geometries. Even with the capacities of present day computers, without dedicated algorithms, we run into excessive computer demands. Domain decomposition methods, and, in the same line of thought, coupled solution methods, aim at avoiding such resource problems. In particular, such methods allow one to take advantage of the possibilities offered by parallel computers. The paper by N. Balin, A. Bendali et al. treats the fundamental issues of the subtle mathematical questions related to domain decomposition methods and, more precisely, concerning the application of Lagrange finite elements. The paper by P. Soudais and A. Barka presents the collaboration between ONERA and Dassault to make two codes work together which had been designed independently. The basic idea, applying to linear problems, is that after having partitioned the computation domain, one can construct the complete and rigorous solution using the most suitable method in any of the sub-domains.

Powerful numerical methods in the time domain

Indeed, the problem of computer resources, alluded to above, appears also in time-domain problems. They may even be more important if one wants to obtain the solution for longer periods of time. It is here that the unwanted effects of classical discretization techniques, in particular numerical dispersion, show up most disturbingly. Higher order discretization techniques have nowadays proved their efficiency in suppressing such undesired effects. The article by G. Cohen, X. Ferrieres and S. Pernet presents an update of the progress made in the context of a collaboration between ONERA and INRIA. This work concerns spectral finite element methods and high-order discontinuous Galerkin methods on hexahedral meshes. The paper by S. Piperno et al. presents some spectacular applications of numerical methods (more specifically, finite volume methods) to the effects of portable telephones.

An oral presentation by G. Sylvand and I. Terrasse has summarized the state of the art as to time-domain integral equations, whereas E. Becache presented fictitious domain methods and space-time mesh refinement methods.

Time harmonic boundary integral equations

The application domain for this kind of integral equation is scattering problems or, more generally, propagation in piecewise homogeneous media. Let us recall that the most evident advantage of such methods consists in reducing the computational effort, most of the time to the surfaces of the objects, and hence, in the discretized problem, diminishing considerably the number of unknowns to be handled. On the other hand, the principal problem with these methods resides in the nature of the matrix of the linear system to solve: it is full, often ill-conditioned, non-symmetric and, at high-frequencies, requires a lot of memory for storage. For high-frequency problems, only iterative solution methods are feasible. In order to reduce the cost of such iterative methods, one can tackle the problem from two sides:

– reduce the cost of a matrix vector product at each iteration, albeit at the cost of some approximation. This is what the by now famous fast multi-pole techniques (FMM) achieve. This is one of the ingredients used in the code of CESTA, presented in the article by K. Mer-Nkonga et al. This code is a good illustration of the integration of theoretical and applied research, because one finds domain decomposition techniques together with integral equation methods in a form presented a few years ago by B. Desprès;
– reduce the number of iterations required for convergence to a desired accuracy. This is the purpose of preconditioning techniques. The paper by D.P. Levadoux shows how sophisticated tools from mathematics (Calderón

projectors and micro-local analysis) can be used to construct preconditioners and analyze their performance. The preconditioner itself also benefits from the FMM technique to minimize its computational overhead.

An oral presentation by J.-P. Martinaud had traced the history of a long collaboration between Thales and CMAP at École Polytechnique (J.C. Nédélec), which has resulted in the development of integral equation methods at Thales.

Asymptotic techniques in electromagnetics

In certain situations, an approach from the purely numerical mathematics point of view is not the best choice to get a good approximate solution efficiently. An alternative approach is to first transform the original model into an approximate model which then is more amenable for numerical computation techniques. This is, for example, the idea behind generalized impedance condition problems for modeling diffraction by obstacles coated with thin layers or obstacles with a high but finite conductivity. In such cases, techniques from asymptotic analysis play a fundamental role in the construction of simplified problems. The article by M. Duruflé, H. Haddar and P. Joly shows a possible construction of such boundary conditions and illustrates the numerical relevance.

Probabilistic models for stochastic interactions

In spite of the great progress in the computation of real-size problems, the predictive power of numerical simulations is still limited by the adequacy of geometrical/physical representations. In particular, at high frequencies (or with very short pulses) relatively small discrepancies between the geometrical models and their real-life counterparts can bring about important, even structural, deviations between computed and actual data. Probabilistic modeling is one way to capture such effects. The paper by B. Michielsen presents a general approach to model the effects of uncertain scattering geometries in uncertain electromagnetic fields. A simple example concerning a stochastic pair of wires in a stochastic electromagnetic wave illustrates how probabilistic modeling can fill in the gap between numerical simulations and real-life situations.

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