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Project-Team POEMS

Wave propagation: Mathematical Analysis and Simulation

Paris - Rocquencourt

THEME NUM

Activity Report

2007

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2. Overall Objectives

2.1. Overall Objectives

The propagation of waves is one of the most common physical phenomena one can meet in nature. From the human scale (sounds, vibrations, water waves, telecommunications, radar) and to the scale of the universe (electromagnetic waves, gravity waves), to the scale of the atom (spontaneous or stimulated emission, interferences between particles), the emission and the reception of waves are our privileged way to understand the world that surrounds us.

The study and the simulation of wave propagation phenomena constitute a very broad and active field of research in the various domains of physics and engineering science.

The variety and the complexity of the underlying problems, their scientific and industrial interest, the existence of a common mathematical structure to these problems from different areas justify together a research project in Scientific Computing entirely devoted to this theme.

The project POEMS is an UMR (Unité Mixte de Recherche) between CNRS, ENSTA and INRIA (UMR 2706). The general activity of the project is oriented toward the conception, the analysis, the numerical approximation, and the control of mathematical models for the description of wave propagation in mechanics, physics, and engineering sciences.
Beyond the general objective of contributing to the progress of the scientific knowledge, four goals can be ascribed to the project:

- the development of an expertise relative to various types of waves (acoustic, elastic, electromagnetic, gravity waves, ...) and in particular for their numerical simulation,
- the treatment of complex problems whose simulation is close enough to real life situations and industrial applications,
- the development of original mathematical and numerical techniques,
- the development of computational codes, in particular in collaboration with external partners (scientists from other disciplines, industry, state companies...)

3. Scientific Foundations

3.1. Scientific Foundations

Our activity relies on the existence of mathematical models established by physicists to model the propagation of waves in various situations. The basic ingredient is a partial differential equation (or a system of partial differential equations) of the hyperbolic type that are often (but not always) linear for most of the applications we are interested in. The prototype equation is the wave equation:

$$\frac{\partial^2 u}{\partial t^2} - c^2 \Delta u = 0,$$

which can be directly applied to acoustic waves but which also constitutes a simplified scalar model for other types of waves (This is why the development of new numerical methods often begins by their application to the wave equation). Of course, taking into account more realistic physics will enrich and complexify the basic models (presence of sources, boundary conditions, coupling of models, integro-differential or non linear terms,...)

It is classical to distinguish between two types of problems associated with these models: the time domain problems and the frequency domain (or time harmonic) problems. In the first case, the time is one of the variables of which the unkonwn solution depends and one has to face an evolution problem. In the second case (which rigorously makes sense only for linear problems), the dependence with respect to time is imposed a priori (via the source term for instance): the solution is supposed to be harmonic in time, proportional to $e^{i\omega t}$, where $\omega > 0$ denotes the pulsation (also commonly, but improperly, called the frequency). Therefore, the time dependence occurs only through this pulsation which is given a priori and plays the rôle of a parameter: the unknown is only a function of space variables. For instance, the wave equation leads to the Helmholtz wave equation (also called the reduced wave equation) :

$$-c^2 \Delta u - \omega^2 u = 0.$$

These two types of problems, although deduced from the same physical modelization, have very different mathematical properties and require the development of adapted numerical methods.

However, there is generally one common feature between the two problems: the existence of a dimension characteristic of the physical phenomenon: the wavelength. Intuitively, this dimension is the length along which the searched solution varies substantially. In the case of the propagation of a wave in an heterogeneous medium, it is necessary to speak of several wavelengthes (the wavelength can vary from one medium to another). This quantity has a fundamental influence on the behaviour of the solution and its knowledge will have a great influence on the choice of a numerical method.

Nowadays, the numerical techniques for solving the basic academic and industrial problems are well mastered. A lot of companies have at their disposal computational codes whose limits (in particular in terms of accuracy or robustness) are well known. However, the resolution of complex wave propagation problems close to real applications still poses (essentially open) problems which constitute a real challenge for applied mathematicians. A large part of research in mathematics applied to wave propagation problems is oriented towards the following goals:

- the conception of new numerical methods, more and more accurate and high performing.
- the treatment of more and more complex problems (non local models, non linear models, coupled systems, ...)
- the study of specific phenomena or features such as guided waves, resonances,...
- the development of approximate models in various situations,
- imaging techniques and inverse problems related to wave propagation.

These areas constitute the main fields of interest for the Project POEMS.

4. Application Domains

4.1. Application Domains

We are concerned with all application domains where linear wave problems arise: acoustics and elastodynamics (including fluid-structure interactions), electromagnetism and optics, and gravity water waves. We give in the sequel some details on each domain, pointing out our main motivations and collaborations.

4.1.1. Acoustics.

As the acoustic propagation in a fluid at rest can be described by a scalar equation, it is generally considered by applied mathematicians as a simple preliminary step for more complicated (vectorial) models. However, several difficult questions concerning coupling problems have occupied our attention recently.

Aeroacoustics, or more precisely, acoustic propagation in a moving compressible fluid, is for our team a new and very challenging topic, which gives rise to a lot of open questions, from the modelling until the numerical approximation of existing models. Our works in this area are partially supported by EADS (and Airbus). The final objective is to reduce the noise radiated by Airbus planes.

Vibroacoustics, which concerns the interaction between sound propagation ans vibrations of thin structures, also raises up a lot of relevant research subjects. Our collaboration with EADS on this subject, with application to the confort of the cockpits of airplanes, allowed us to develop a new research direction about time domain integral equations.

A particularly attractive application concerns the simulation of musical instruments, whose objectives are both a better understanding of the behavior of existing instruments and an aid for the manufactoring of new instruments. The modeling and simulation of the timpani and of the guitar have been carried out in collaboration with A. Chaigne of ENSTA. We intend to initiate a new collaboration on the piano.

4.1.2. Electromagnetism.

This is a particularly important domain, first because of the very important technological applications but also because the treatment of Maxwell's equations poses new and challenging mathematical questions.

Applied mathematics for electromagnetism during the last ten years have mainly concerned stealth technology, electromagnetic compatibility, design of optoelectronic micro-components or smart materials.

Stealth technology relies in particular on the conception and simulation of new absorbing materials (anisotropic, chiral, non-linear...). The simulation of antennas raises delicate questions related to the complexity of the geometry (in particular the presence of edges and corners). Finally micro and nano optics have seen recently fantastic technological developments, and there is a real need for tools for the numerical simulation in these areas.

Our team has taken a large part in this research in the past few years. In the beginning, our activity was essentially concerned with radar furtivity (supported by the French Army and Aeronautic Companies). Now, it is evolving in new directions thanks to new external (academic and industrial) contacts:

- We have been developing since 2001 a collaboration with ONERA on EM modeling by higher order methods (theses of S. Pernet and M. Duruflé).
- As partners of ONERA, we have been selected by the CEG (a research organism of the French Army) to contribute to the development of a general computational code in electromagnetism. The emphasis is on the hybridization of methods and the possibility of incorporating specific models for slits, screens, wires,...
- Optics is becoming again a major application topic. In the past our contribution to this suject was quite important but remained at a rather academic level. Our recent contacts with the company ATMEL (on the modelling of optical filters) and with the Institut d'Electronique Fondamentale (Orsay) (we have initiated with them a research program about the simulation of micro and nano opto-components) are motivating new research in this field.
- Multiscale modelling is becoming a more and more important issue in this domain. In particular, in collaboration with the LETI(CEA) in Grenoble, we are interested in simulated devices whise some of the geometric characterictics are much smaller than the wavelength.

4.1.3. Elastodynamics.

Wave propagation in solids is with no doubt, among the three fundamental domains that are acoustics, electromagnetism and elastodynamics, the one that poses the most significant difficulties from mathematical and numerical points of view. Our activity on this topic, which unfortunately has been forced to slow down in the middle of the 90's due to the disengagement of French oil companies in matter of research, has seen a most welcomed rebound through new academic and industrial contacts.

The two major application areas of elastodynamics are geophysics and non destructive testing. A more recent interest has also been brought to fluid-stucture interaction problems.

- In geophysics, one is interested in the propagation of elastic waves under ground. Such waves appear as natural phenomena in seisms but they are also used as a tool for the investigation of the subterrain, mainly by the petroleum industry for oil prospecting (seismic methods). This constitutes an important field of application for numerical methods. Our more recent works in this area have been motivated by various research contracts with IFP (French Institute of Petroleum), IFREMER (French Research Institute for the Sea) or SHELL (which have supported, at least partially, the PhD theses of S. Fauqueux, A. Ezziani and J. Diaz).
- Another important application of elastic waves is non-destructive testing: the principle is typically to use ultra-sounds to detect the presence of a defect (a crack for instance) inside a metallic piece. This topic is the object of an important cooperation with EDF (French Company of Electricity) and CEA Saclay in view on the application to the control of nuclear reactors. This collaboration has motivated some of the most important and innovative scientific achievements of the project with the theses of C. Tsogka, G. Scarella and J. Rodriguez.

  At a more academic level, we have been interested in other problems in the domain of elastic waves in plates (in view of the application to non-destructive testing) through our participation to the GDR Ultrasons. In this framework, we have developped our resarches on multi-modal methods, exact transparent conditions or shape reconstruction of plates of variable cross section.
- Finally, we have recently been led to the study of fluid-solid interaction problems (coupling of acoustic and elastic waves through interfaces) as they appear in underwater seismics (IFREMER) and stemming from ultra-sound propagation in bones (in contact with the Laboratoire d'Imagerie Paramétrique of Paris VI University).

4.1.4. Gravity waves.

These waves are related to the propagation of the ocean swell. The relevant models are derived from fluid mechanics equations for incompressible and irrotational flows. The applications concern in large part the maritime industry, if particular the questions of the stability of ships, sea keeping problems, wave resistance,... The application we have recently worked on concerns the stabilization of ships and off-shore platforms (contract with DGA).

5. Software

5.1. Advanced software

We are led to develop two types of software. The first category is prototype softwares : various softwares are developed in the framework of specific research contracts (and sometimes sold to the contractor) or during PhD theses. They may be also contributions to already existing softwares developed by other institutions such as CEA, ONERA or EDF. The second category is advanced software which are intended to be developed, enriched and maintained over longer periods. Such sofwares are devoted to help us for our research and/or promote our research. We have chosen to present here only our advanced softwares.

- **MELINA :** This software has been developed under the leadership of D. Martin for several years in order to offer to the researchers a very efficient tool (in Fortran 77 and object oriented) for easily implementing finite element based original numerical methods for solving partial differential equations. It has specific and original potential in the domain of time harmonic wave problems (integral representations, spectral DtN conditions,...). Nowadays, it is fully functional in various application areas (acoustics and aeroacoustics, elastodynamics, electromagnetism, water waves). It is an open source software with on line documentation available at

  http://perso.univ-rennes1.fr/daniel.martin/melina/

  The software is regularly used in about 10 research laboratories (in France and abroad) and number of research papers have published results obtained with MELINA (see the Web site). Moreover, every 2 years, a meeting is organized which combines a workshop which teaches new users with presentations by existing users.
  During the last four years, apart from various local improvements of the code, new functionalities have been developed:

  – Higher order finite elements (up to 10^{th} order),

  – Higher order quadrature formulae,

  – DtN boundary conditions in 3D.

  A new C++ version of the software is under development. We will take advantage of this evolution for extending the class of finite elements (mixed elements, tensor valued elements, ...).

- **MONTJOIE :** This is a software for the efficient and accurate wave propagation numerical modeling in both time dependent or time harmonic regimes in various domains of application : acoustics, aeroacoustics, elastodynamics and electromagnetism . It is based essentially on the use of quadrilateral/hexaedric conforming meshes and continuous or discontinuous Galerkin approximations, The use of tensor product basis finctions coupled to judicious numerical quadrature techniques leads to important gains in both computing time and memory storage. Various techniques for treating unbounded domains have been incorporated : DtN maps, local absorbing conditions, integral representations and PML's.

We have written an interface for the use of otjher libraries : SELDON, a C++ linear algebra library (interfaced with BLAS and LAPACK) used for iterative linear solvers, MUMPS and UMFPACK for direct linear solvers, ARPACK for eigenvalue computations. The mesh generation is not part of the code. It can be done with Modulef, Gmsh, Ghs3D or Cubit.

This code has been deveploped by Marc Duruflé during his PhD thesis. Some other contributors have brought more specific enrichments to the code.

- **LSM** : This software is a Fortran-90 code coupled with a Matlab interface. It solves the inverse acoustic and electromagnetic scattering problem using the Linear Sampling Method and the Tikhonov regularization. This code has been developed by H. Haddar. A parallel version has been produced by M. Fares from Cerfacs. This code was provided to and used by researchers at the university of Delaware (E. Darrigrand, P. Monk), Cerfacs (M. Fares) and the University of Genova (M. Piana). A 2-D version of this code coupled with the forward solver of the Helmholtz equation (provided by F. Collino) is under construction and should be available on the project web-site before the end of 2004. ICI- ACTUALISER.

6. New Results

6.1. Introduction

We have chosen to group our research into 7 distinct parts. Of course this partition is somewhat arbitrary and overlap is possible (a given work could appear in several categories).

6.2. Numerical methods for time domain wave propagation

6.2.1. Higher-Order Methods in space

Participants: Mogane Bergot, Gary Cohen, Edouard Demaldent, Marc Duruflé, Patrick Joly.

This topic has been developed in our team for more than 10 years (see the previous activity reports of ONDES and POEMS). The overall objective is toconstruct discretization methods (finite differences, finite elements, mixed finite elements, discontinuous Galerkin Methods) for time dependent wave problems that allow us to get arbitrary accuracy, lead to explicit schemes and aim at minimizing both the computational time and memory storage. This year our contributions have been the following:

- M. Duruflé and P. Joly have studied in collaboration with P. Grob (post doc at Québec) the theoretical aspects of the use of spectral finite element for the scalar wave equations in general hexaedric meshes. They have in particular analyzed the influence of quadrature formulas in this context. The difficulty is the fact that the elementary transform between the reference element (the unit cube) and the current element (a deformed cube) is in general nonlinear, which reflect the fact that the faces of the elements are in general not plane. They have compared theoretical error estimates with numerical observations. The results and the agreement between theoretical results depend on various parameters among which the nature of the quadrature formula and the space dimension. They demonstrate that the use of general hexahedric meshes may (or may not) destroy the optimal accuracy obtained with parallelepipedic meshes.
- M. Bergot has started her PhD in September. She is working on the hybridization of spatial meshes (typically meshes in the 3D space that mix the use of tetrahedra, hexaedra, pyramids and prism) in the context of continuous and discontinuous finite element approximations of time dependent problems. One of the new aspects is the construction of local finite element spaces and related quadrature formulas on elements of non-standard shape.
- E. Demaldent is pursuing (at ONERA) his PhD about the use of high order polynomial approximations for the discretization of integral equations arising in time harmonic scattering problems.

6.2.2. Accurate numerical resolution of Vlasov-Maxwell's equations

Participants: Gary Cohen, Alexandre Sinding, Marc Duruflé.

This is a new topic we have initiated this year. A. Sinding has begun his PhD Thesis of the resolution of time dependent Vlasov-Maxwell's equations in the framework of a contract with the Centre d'Etudes de Gramat. The objective of the thesis is the coupling between higher order hexaedric finite elements for Maxwell's equations with a Particle in Cell Method for The Vlasov equations. He his first looking at the 2d case.

During his post-doc at San Dia Labs, M. Duruflé is investigating the problem in the axi-symmetric case. An original high-order finite element method enabled us to reach a quasi-constant computational time cost according to the order. Although this is less efficient than low-order PIC methods for basic cases, an advantage is expected for more complex cases. The extension to 3-D is also being studied.

6.2.3. Representation of solutions to hyperbolic systems

Participant: Jérome Le Rousseau.

We are interested in an original representation formula for the solutions to hyperbolic systems by a multi-product of Fourier integral operators (FIO). Here we mean that an approximation of the solution is given by a finite product of FIOs and the solution is exactly recovered by passing to the limit (in the number of operators in the product). The tools employed to obtain such results are those of microlocal analysis. This representation formula is interesting because each FIO in the product is given in a simple and explicit manner. As a consequence, this representation leads to natural numerical schemes, which can be made computationally efficient with additional approximations. One of the motivation for this work is seismic imaging. This research effort was first conducted for scalar equations. In 2007, we extended this approach to the case of symmetric and symmetrizable systems. This extension is far from being straightforward, in particular as one is then confronted to algebraic operations on matrices, for the phases and amplitudes of the operators, that do not commute. We were also led to introducing a new type of FIOs with a complex matrix phase. For such operators, classical composition theorems do not apply and cannot be directly generalized.

6.2.4. Higher order time discretization of second order hyperbolic problems

Participants: Jerónimo Rodríguez, Patrick Joly.

This is a more recent topic that P. Joly initiated last year in collaboration with Jean-Charles Gilbert (Project Estime). We worked on the construction of new time discretization procedures for second order hyperbolic problems, of the form

$$\frac{d^2u}{dt^2} + \mathcal{A}u = 0, \tag{1}$$

where $\mathcal{A}$ is a linear unbounded positive selfadjoint operator in some Hilbert space V. We have pursued this work with J. Rodríguez. Let us recall that the starting point of this research was study the even order $(2m)$ schemes obtained by the modified equation method. We show that the corresponding CFL upper bound for the time step remains bounded when the order of the scheme increases, which can be somewhat penalizing. This observation leads us to propose variants of these schemes constructed to optimize the CFL condition: this is formulated as an optimization problem in a space of polynomials of given degree. This problem can be analyzed in detail. In particular, we have proven the existence and uniqueness of the solution, given necessary and sufficient conditions of optimality and provided an algorithm which provides the optimal schemes for $m \leq 10$ (some numerical difficulties - probably linked to round-off errors - are still encountered for larger values of m). We were able to prove that this type of scheme, one is able to recover an arbitrary accuracy in time for almost no cost, asymptotically with respect to large m's.

These schemes have been implemented and tested on the model problem of the scalar wave equation with Dirichlet boundary conditions when a higher order Discontinuous Galerkin method with centered fluxes is used for the space discretization. Our first numerical results are quite encouraging and confirm the theoretical results. However, the effective accuracy os these schemews remains to be quantified. It also remains to extend and test them in less academic cases (other boundary conditions, other equations, ...)

6.2.5. The wave equation with fractional order dissipative terms

Participants: Houssem Haddar, Jing-Rebecca Li.

This is a work in collaboration with D. Matignon. The dissipative model which describes acoustic waves traveling in a duct with viscothermal losses at the lateral walls is a wave equation with spatially-varying coefficients, which involves fractional-order integrals and derivatives. The typical application is the numerical modeling of wind musical instruments. The main goal of our investigations is to propose an efficient numerical discretization of the coupled model, that avoids for instance the storage of the solution during past steps which would be penalizing for long time simulations. Our approach is based on so-called diffusive representations of the fractional integral where, roughly speaking, the fractional-order time kernel in the integral is represented by its Laplace transform. This allows for efficient time domain discretizations because the value of integral at each time step can be updated from the value at the previous time step by operations which are local in time, contrary to a naive discretization of the fractional integral. These representations require however the evaluation of an integral over the Laplace variable domain. We propose and analyze two schemes based on the choice of the quadrature rule associated with this integral.

The first one is inspired by the continuous stability analysis of the initial boundary value problem associated with coupled system: wave equation-diffusive representation. The scheme is constructed so that it preserves the energy balance at the discrete level. This is done however at the expense of a loss of accuracy with the simulation time. The second approach is numerically more efficient and provides uniform control of the accuracy with respect to the simulation time. The idea of this approach is inspired by the work of Greengard and Lin: the convolution integral is split into a local part and a historical part, where for the latter one can exploit the exponential decay of the Laplace kernels to choose quadrature rules that provide uniform error in time. Essentially, the number of quadrature points in the Laplace domain is $O(-\log(\Delta t))$ where Δt denotes the time step. Thus, if M is the number of time steps, the numerical scheme we propose requires $O(M\log(M))$ work and $O(\log(M))$ memory, compared to $O(M2)$ work and $O(M)$ memory of a naive discretization. Let us notice however that even though more efficient and seems to be numerically stable under the standard CFL, no discrete energy balance has been found for the second scheme.

6.2.6. Coupling Retarded Potentials and Discontinuous Galerkin Methods for time dependent wave propagation

Participants: Patrick Joly, Jerónimo Rodríguez.

Discontinuous Galerkin (DG) methods have recently gained a great attention for the resolution of time dependent wave propagation problems. These methods benefit in particular from a great flexibility in terms of $h-p$ adaptivity. Moreover, they can be applied for solving PDE's such as linearized Euler equations (being aeroacoustics one of the applications we have in mind) where the presence of convection terms makes difficult the application of finite elements, for example.

On the other hand, many problems related with wave propagation are posed on unbounded domains. This raises the question of bounding artificially the computational domain. The increasing computational power together with the progress of rapid algorithms like the fast multipole method make now possible, at least when the exterior domain is homogeneous, the use of exact or transparent boundary conditions. Such a condition relies on an explicit representation of the solution on the exterior domain Ω_e from its traces on the boundary Γ. In 3D, these formulas are known as retarded potential representations (RP).

That is why one is naturally lead to investigate the question of coupling these two techniques. One of the major difficulties is to guarantee a priori the stability of the resulting scheme. Let us present this method on the model problem of the acoustic wave equation (but it can be generalized to other Friedrichs' systems).

The problem is formulated as a system between the PDE's for the pressure p and the velocity v in the interior domain Ω_i and $\varphi \equiv p_{|\Gamma}$ and $\psi \equiv (\mathbf{v} \cdot \mathbf{n})_{|\Gamma}$ on its boundary Γ, namely, the traces of the solution on the interface. More precisely, we couple the interior PDE's with the transparent condition written with the help of the classical Calderón-Zygmund operator associated to the wave equation. This is a space-time integral operator acting on functions defined on $\Gamma \times \mathbb{R}^+$ whose expression is computed from the fundamental solution of the wave equation. We can write a particular variational formulation of which is of *DG type* for the interior equation and of space-time nature for the boundary equations. The most delicate step is the space-time discretization of this formulation, combining DG in space and finite differences in time for the first equation and a space-time Galerkin approach for the second. The resulting scheme is explicit at the interior of the domain, subject to a CFL condition, and implicit on the boundary through the inversion of a sperse matrix whose small bandwidth determined by the time step. The key point is to design the discretization procedure in order to guarantee a discrete energy identity that is consistent with the continuous one and yields stability under the CFL condition of the interior scheme (in other words, the stability condition is not affected by the coupling with the transparent boundary conditions).

6.3. Time-harmonic diffraction problems

6.3.1. Harmonic wave propagation in locally perturbed infinite periodic media

Participants: Sonia Fliss, Patrick Joly.

This is the subject of the PhD thesis of Sonia Fliss. Two main domains of application are concerned:

- the propagation of electromagnetic waves in photonic crystals, a subject that we study in the frameworh of the ANR Project SimNanoPhot, in collaboration with the Institut d'Électronique Fondamentale (IEF, Orsay University),
- the propagation of ultrasonic waves in composite materials, in view of their nondestructive testing, a subject developped within a collaboration with EADS.

During the first half of the thesis, the main principles and theoretical bases of a numerical method for treating the scalar 2D problem have been settled. These aspects have resulted into an article to appear in *Applied Numerical Mathematics* and various presentations in several international conferences.

The method is quite involved and we refer the reader to the two previous activity report for more details.This year, the full method has been successfully implemented. The treatment of the non absorbing case has necessited specific developments that correspond to a numerical limiting absorption principle (see figure 1).

On the application side, we have brought a particular attention of the transmission of an incident electromagnetic wave in the vacuum (typically a Gaussian beam) inside a photonic crystal. This has been the opportunity to compare our method with the method used at IEF. The first results of this comparison are quite encouraging (see figure 2).

This research offers a number of interesting perspectives and developments from theoretical, numerical and practical points of view, which should justify a second PhD thesis on the subject.

6.3.2. Time harmonic wave propagation in elastic periodic waveguides

Participants: Jeremy Dardé, Sonia Fliss, Patrick Joly.

The method introduced by Fliss-Joly-Li for acoustic waveguides has been extended to 2D elastic waveguides during the internship of J. Dardé. The main lines and theoretical features of the method remain essentially the same as for the scalar case. The additional complexity is essentially linked to the vectorial nature of the unknowns. The resulting computational code has been successfully tested. In particular, in the case of a homogeneous waveguide, one can check that one reconstruct automatically the well-known Lamb modes. As a consequence, in this particular case, this method is also an alternative to the (more analytical) method developed in the PhD thesis of V. Baronian (see section 6.5.2).

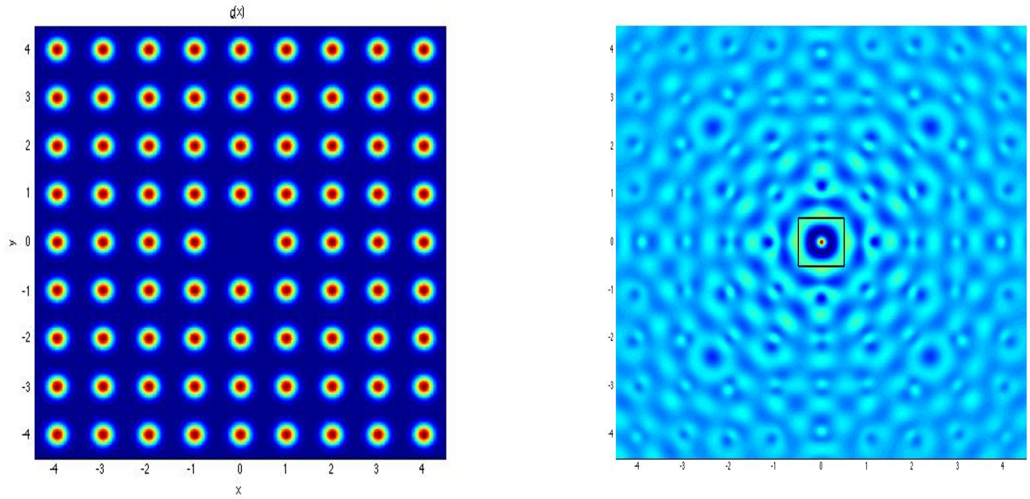

Figure 1. The propagation medium (left). A numerical Green's function (right)

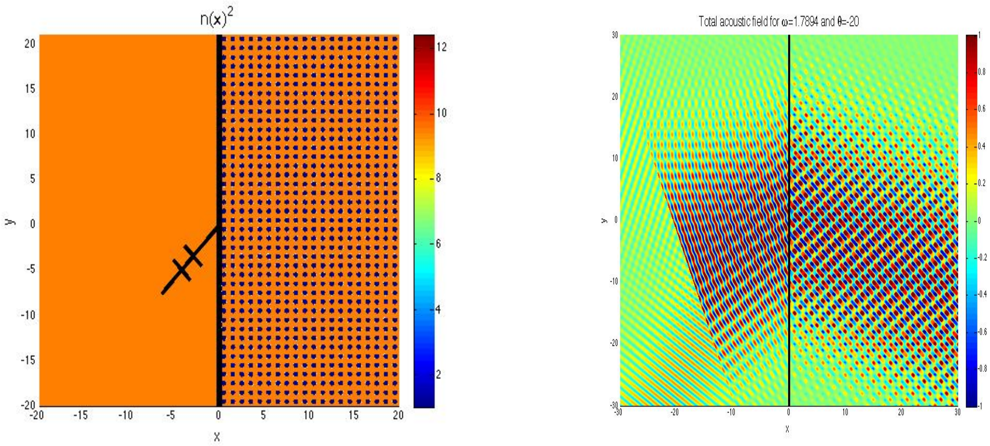

Figure 2. The propagation medium (left). Transmission of a Gaussian beam (right)

6.3.3. Reduced basis method for harmonic wave propagation problems

Participant: Jeronimo Rodríguez.

This work is developed in collaboration with J. S. Hesthaven (Brown University) and Y. Maday (Paris VI). Let us recall is that the principle of the method is to compute efficiently, i.e. at low cost, the solution of (stationnary) pde's depending on one or several parameters, for a large number of value of these parameters. The principle is to determine an ad hoc basis, of small dimension, for a Galerkin approximation. This basis is constructed by solving the problem for a small set of well selected parameters. Moreover, this selection can de done optimally with respect to some criteria. We refer the reader to the activity report of last year for more details.

Time harmonic wave propagation are a natural field of application for this type of method, the frequency ω providing a natural parameter. In the near future, we would like to test this approach for the implementation of the method developed in the thesis of S. Fliss (see section 6.3.1) for wave propagation media : one important step in the resolution of a lot of k-dependent cell problems where k is the quasi-periodic wave number.

6.3.4. Modeling of meta-materials in electromagnetism.

Participants: Anne-Sophie Bonnet-Ben Dhia, Patrick Ciarlet, Carlo Maria Zwölf.

Meta-materials can be seen as particular dielectric media whose dielectric and/or magnetic constant is negative, at least for a certain range of frequency. This type of behaviour can be obtained, for instance, with particular periodic structures. The theory and numerics for dealing with this type on media is a new challenge for applied mathematicians. This is the case of the transmission between two media with opposite sign dielectric and/or magnetic constants, the subject of the PhD thesis of C. M. Zwölf, defended in November. This year, on a simplified scalar model, we tested numerically the naïve finite element approach to validate the “more special” three-field formulation we introduced last year. Surprisingly, the naïve approach provided the better results, despite of the lack of coercivity of the bilinear form of the problem. Fortunately, we were able to understand why thanks to the Strang's theory for non conforming approximation. The case of 3D Maxwell's equation is much less clear and deserves further investigation.

6.3.5. Robust computation of eigenmodes in electromanetism

Participants: Patrick Ciarlet, Grace Hechme.

This is a work in collaboration with A. Buffa (Pavia). To overcome the traditional difficulty linked to the apparition of spurious modes of the Maxwell's operator, we have proposed, analyzed and implemented a method based on a “saddle-point” formulation of the eigenvalue problem.

6.3.6. Scattering by a locally non uniform open waveguide

Participants: Christophe Hazard, Anne-Sophie Bonnet-Ben Dhia.

The aim of this work, in collaboration with Lahcen Chorfi and Ghania Dhakia from University of Annaba, in to prove the existence and uniqueness of the solution for the scattering by a localized defect in an open acoustic waveguide, when a suitable radiation condition at infinity. The analysis makes use ot a special generalized Fourier transform associated to the spectral decomposition of the self-adjoint operator associated to a transverse cross-section of the unperturbed waveguide. This needs to be justified outside the classical L^2 framework : the transform has to be extended to distributions. This is a technical difficulty that has been solved this year, which should permit us to complete the theory.

6.3.7. Time harmonic aeroacoustics

Participants: Anne-Sophie Bonnet-Ben Dhia, Eve-Marie Duclairoir, Vincent Ledain, Jean-François Mercier.

This topic provided the subject of the PhD of Eve-Marie Duclairoir, defended in March. In this work, we have designed a very specific method for computing sound propagation in stationnary flows in the time harmonic regime. The main characteristics of this method are

- Galbrun's equations (Lagrangian displacement and eulerian coordinates) are used for the mathematical model.
- A regularized variational formulation, allowing the use of nodal finite elements, is used for overcoming the lack of H^1 coercivity of the original model. This leads to solve a coupled system whose unknowns are the displacement field and the vortex.
- In the particular case where the Mach number is small, a low Mach number approximate model can be used to "decouple" and simplify the calculations of the vortex and of the displacement field.

This year, error estimates have been established for the low Mach model, which has been validated numerically during the internship of V. Ledain.

The thesis of E. M. Duclairoir concerned the 2D model with a parallel reference flow. The more general case (general flows, 3D, ...) is being developed in collaboration with CERFACS.

6.4. Absorbing boundary conditions and absorbing layers

6.4.1. Exact bounded PML's with singularly growing absorption

Participants: Eliane Bécache, Andres Prieto.

The work on "exact" PML methods with singularly growing absorption for time dependent wave problems (including the treatment of corners) is being finalized (for more details, see the activity report of last year).

6.4.2. Absorbing boundary conditions and PML's for linear water waves

Participants: Gary Cohen, Sébastien Impériale, Patrick Joly.

During its internship, Sébastien Impériale has revisited the question of artificial boundary conditions for the propagation of linear water waves.

In a first part of his work, he has implemented the local in time - nonlocal in space absorbing boundary conditions proposed by K. Dgaygui and P. Joly in an old work. With standard discretization procedures, one encounters difficulties to represent properly the long time behaviour of the solution. This is due to resonant modes introduced by the boundary conditions that are not "excited" in the continuous model but are present in the numerical computations. These parasitic solutions can however be attenuated by modifying the time discretization procedure.

In the second part, he has extended PML's machinery to the mathematical model of linear water waves, which is not completely straightforward, due to the non hyperbolic nature of this problem. The associated theory is still open but the numerical results obtained with this alternative method are much better than those with the local absorbing conditions. In particular, at large time, the undesirable resonance phenomena are no longer present.

6.4.3. Using PML techniques for spectral problems

Participants: Anne-Sophie Bonnet-Ben Dhia, Eliane Bécache, Benjamin Goursaud, Christophe Hazard, Andres Prieto.

This is a very new topic motivated by our work of the modelization of tapers (the transition between two open waveguides with different geometrical and / or physical characteristics) in the framework of the ANR SinNanoPhot (with IEF at Orsay). The idea is to investigate how the PML machinery can be used for discretizing (at least in an approximate sense, which remains to be clarified from the theoretical point of view) the spectrum of the transverse operator associated to a section of an openwaveguide, with the objective to use the associated "eigenmodes" for constructing a multimodal approximation (see also section 6.5.1). Physically, this amounts to replace the continuum of radiation modes that contribute to the continuous part of the spectrum of the original operator (i. e. without PML's) by the so-called leaky modes (or at least an approximation of thgem due to the truncation of the PML) that form a discrete set. This approach has some similarities with the singularity expansion method, already studied at Poems for the solution of time dependent problems ; here the time variable is "replaced" by the abcissa along the waveguide. This is the subject of the PhD thesis of B. Goursaud who started in October.

6.5. Waveguides and resonances

6.5.1. The multimodal method

Participants: Christophe Hazard, Anne-Sophie Bonnet-Ben Dhia, Eric Lunéville.

The development and theory the multimodal method for closed acoustic waveguide with slowly (at least smoothly) varying cross-section have been completed this year. The corresponding results have been submitted for publication. Our next developments on this topic will concern the much more difficult situation of open waveguides with varying cross-section as announced in section 6.4.3.

6.5.2. Elastic waveguides

Participants: Vahan Baronian, Anne-Sophie Bonnet-Ben Dhia, Eric Lunéville.

This is the subject of the PhD thesis of V. Baronian, in collaboration with the CEA (Saclay). We have developed a method to solve the diffraction problem of Lamb waves in a 2D elastic waveguide. The diffraction is produced by a defect, for instance a crack. We refer to the previous activity report for the details of the method. Let us simply remind that the key difficulty of the problem is the reduction to a bounded domain containing the defect. We construct a "DtN-likde" transparent boundary conditions with a very specific choice of boundary unknowns and a special modal decomposition that makes use of the so-called Fraser bi-orthogonality relation. A 2D numerical code has been implemented and validated. The more recent progress concern the theory: we have been able to show that the mathematical model used for the numerical method entered a Fredholm framework, which was far from obvious. This should allow us to complete the numerical analysis.

6.6. Asymptotic methods and approximate models

6.6.1. Asymptotic models for thin slots

Participants: Patrick Joly, Adrien Semin.

This on going research in the heritage of the PhD thesis of S. Tordeux, defended in 2005. It has two parts:

- In collaboration with D. Sanchez, we are working on 2D-3D approximate model for the propagation of electromagnetic waves in the juntion of a thin slot with a 3D medium (typically a half-space). The model had been proposed last year and its consistency and accuracy has been completely analyzed. To complete the theory, we are facing a new difficulty linked to the stability analysis. We are currently working on this open question related to the lack of compactness of $H(curl)$ spaces and to exploit the free divergence condition. For a given value of the width ε of the slot, this is a classical question. Here, the difficulty is to obtain uniform compactness with respect to ε.

- With the internship and the PhD thesis of A. Semin, who started in September, we are studying network of thin slots. Our objective is to understand mathematically the well known 1D limit model with Kirchhoff transmission conditions at the nodes of the network and go beyond by proposing improved models. This can be done via the asymptotic analysis using matched asymptotics. We have considered the 2D case and have been able to propose a second order model (the limit model being first order): the particularity is that, contrary to Kirchhoff conditions, the new transmission conditions "see" (via the resolution of auxiliary elliptic problems, as a pre-processing of the model) the geometry of the network (for instance the angle between two branches) and not only its topology (typically the number of branches connected to the same node). This model has been implemented, validated by comparison with the full model and analyzed mathematically (error estimates). Both theory and numerics work in the time harmonic case or the time dependent case. Moreover, the approximate model is of interest to understand and interpret numerical observations made with the full 2D model.

6.6.2. Asymptotic models for thin wires

Participants: Xavier Claeys, Patrick Joly, Houssem Haddar, Francis Collino.

This is the topic of the PhD thesis of X. Claeys. The new results for this year are the following

- The numerical approach proposed last year for the 2D problem (diffraction of an acoustic wave by a very small obstacle) has been successfully extended to the 3D acoustic case (the scatterer is a "true" wire and the Dirichlet condition is imposed on its boundary) for both time dependent and time harmonic regimes. Let us recall that this method is based on the combination of an improved "Holland like" model (constructed from the asymptotic expansion of the solution of the exact model with respect to the thickness of the wire), a fictitious domain formulation and an enriched Galerkin formulation. With respect to the 2D case, the main novelty is that the Lagrange multiplier introduced to treat the boundary condition is now a 1D function that needs to be discretized and the enrichment space is built with tensor products of functions of the curvilinear abcissa along the wire with ad hoc singular shape functions of the distance to the wire. The discretization in the curvilinear coordinate is done thanks to a spectral method using Legendre polynomials. A computational code has been implemented and the first numerical results are quite satisfactory in both terms of accuracy and robustness (absence of numerical locking when ε tends to 0). The corresponding numerical analysis is in progress.
- The theory has been extended to Maxwell's equations. The major difficulty is to produce (and even more justify mathematically) the good asymptotic expansion of the exact solution via matched asymptotic expansions. This work requires sophisticated mathematical tools such as Mellin transform, complex analysis methods,... The actual state of our work should lead very soon into a complete theory in the case where an absorbing medium is considered. The limit case introduces a new difficulty linked to the stability analysis when ε tends to 0 (the good functional framework has to be determined).

6.6.3. Multiscale modelling in electromagnetism.

Participants: Bérangère Delourme, Houssem Haddar, Patrick Joly.

This new topic is developed in collaboration with the CEA (LETI) in Grenoble and constitutes the subject of the PhD thesis of Bérangère Delourme who benefited from a scholarship from CEA. The application we have in mind, proposed by Michelin, is the modelling of electromagnetic waves inside a tyre. The main difficulty of the problem is the presence of two thin cylindrical layers of helicoidal metallic wires regularly and periodically spaced in the azimuthal direction. The scales of the problem (thickness of wires, large number of wires) make the problem out of reach with standard numerical approaches. Our idea is to develop and compare two methods which would incorporate more and more a priori mathematical analysis:

- Exploit the azimuthal periodicity of the medium by using a discrete Floquet-Bloch transform. This leads to solve a finite (but possibly large - depending on the frequency) number of reduced cell problems. This approach has been successfully implemented and tested during the internship of B. Delourme.
- Exploit the small thickness of the wire and the small size of the periodicity cell by buolding approximate models in which the thin layer of wires would be replaced by an effective transmission condition. This can be done via asymptotic techniques by combining homogenization methods with matched asymptotics or multiscale expensions.

6.6.4. Quasi-singularities for Maxwell's equations

Participants: Patrick Ciarlet, Samir Kaddouri.

This was the subject of the PhD thesis of Samir Kaddouri, which was defended in March. The work consisted in understanding how the singularities of an electromagnetic field appear when one considers the scattering by a family of smooth obstables who tend to a non smooth one presenting reentrant corners. The analysis is done with the technique of matched asymptotics.

6.6.5. Approximate models in aeroacoustics

Participants: Anne-Sophie Bonnet-Ben Dhia, Marc Duruflé, Patrick Joly, Lauris Joubert.

This is the subject of the PhD thesis of Lauris Joubert in the continuation of the PhD thesis of K. Berriri.

We studied the propagation of acoustic waves in a duct in the presence of a laminated flow when the width of the duct is small with respect to the wavelength. Under the assumption that the Mach profile of the flow us obtained by a scaling of the Mach profile of a reference flow, we establish formally a quasi-1D model limit which appears to be of integro-differential type : it is local in the longitudinal direction and non-local in the transverse one (in scaled coordinates).

The study of the well-posedness of the limit problem is a delicate issue. This is due to the non-normality of the generator A of the underlying semi-group. We were able to give sufficient conditions (about the profile of the reference flow) for the well-posedness of the limit problem but also sufficient conditions for the strong ill-posedness of this problem. As a by product, we are able, by a long wave asymptotic analysis, to get new results on Kelvin-Helmholtz type hydrodynamic instabilities in compressible fluids.

This analysis points out the difficulties for the construction of a stable discretization scheme but also suggests some ideas to get such a scheme. The goal is to obtain a kind of spectral representation of the solution based on a diagonalization of the operator A, whose spectrum is real when the limit problem is well posed.

6.7. Imaging and inverse problems

6.7.1. The RG-LSM algorithm with an analytic continuation method

Participants: Houssem Haddar, Ozgur Ozdemir.

The RG-LSM algorithm has been introduced by Colton-Haddar as a reformulation of the linear sampling method in the cases where measurements consists of Cauchy data at a given surface. The formulation of the algorithm is based on the reciprocity gap functional on the measurement locations. The advantage of this algorithm was to avoid the need of considering the full inverse scattering problem (requiring for instance the computation of the background Green tensor) and in some sense concentrate only on what happening inside the probed region. The new formulation has also permitted to embed usual sampling method into a more general framework that would be interest in the study of the method.

This method is for instance well suited to imaging of embedded targets when the measurements can be achieved at the interface of the interrogated medium. However, in many practical applications, like imaging of embedded facilities in the soil, these measurements cannot be easily obtained. Only measurement of the scattered field in the air would be feasible. The problem under investigation is to study how accurate would be the coupling of the RG-LSM algorithm with an analytic continuation method that would provide the Cauchy data from the scattered field. In a first approach we considered the simplified case of doubly layered medium where the analytic continuation procedure can be simply achieved with help of longitudinal Fourier transform. The 2-D case have shown that a substantial gain in cpu time can be obtained as compared with applying the linear sampling method with background Green tensor of doubly layered medium being computed. The accuracy is roughly the same. The next steps of this ongoing work will be:

- Consider the case of rough interfaces where the continuation method can be achieved by coupling the Fourier transform with a Taylor series expansion
- Study the stability of the continuation method and quantify the error in terms of the frequency
- Generalize theses results to the electromagnetic problem

6.7.2. Identification of effective dielectric properties using sampling algorithms

Participants: Houssem Haddar, Ridha Mdimegh.

It is well known that sampling algorithms only provide the geometry of the sought inclusion from multi-static data. However in some special cases we showed that a post processing of this algorithm also provide informations on the physical parameters of the inclusions. The first one is the case where the obstacles size is mall compared to the wavelength. It is well known in that case that the center of the inclusion can be uniquely determined from the range of the far field operator associated with the asymptotic expression of the farfields. The MuSiC approach based on projection on the null space of the measurement's matrix or the linear sampling approach based on computing a regularized solutions to a testing equation, can be used to localize these centers. The advantage of the linear sampling method is that the computed solution can be also used to evaluate the Herglotz wave at the sampling point. The latter quantity is shown to be sufficient to determine the effective properties of the inclusions. The advantage of this approach is that it can also generalize to the case of RG-LSM algorithm where instead of the Herglotz wave one evaluates the used approximating operator at the sampling point.

We shall use similar approach to the case of extended targets and anisotropic inclusions.

6.7.3. Transmission Eigenvalues and application to the identification problem

Participant: Houssem Haddar.

The so called interior transmission problem plays an important role the inverse scattering problem from (anisotropic) inhomogeneities. Solution to this problem associated with singular sources can be used for instance to establish uniqueness of the reconstruction of anisotropic inclusion shape. It is well known also that the injectivity of the far field operator used in sampling method is equivalent to the uniqueness of solution to this problem.

In a first work, in collaboration with F. Cakoni we studied this interior transmission problem in the case of anisotropic Maxwell's equations and with possibly coated parts (that is modeled with an impedance boundary condition). The results extend the one previously established by Haddar to the case where the index norm is less than one and also show that the set of the eigenvalues for this transmission problem is at most discrete. Showing the existence of these eigenvalues is still an open problem due to the fact that the operator involved is not self-adjoint.

The analysis also showed that some lower bounds can be obtained on these eigenvalues in terms of the inhomogeneity shape and the index norm. This was the starting point of the idea of exploiting the eigenvalues to get information on the index of the sought inhomogeneity. More precisely, using the sampling operator with fixed sampling point and by varying the frequency one can localize the presence of eigenvalues when the norm of the solution becomes large. This procedure has been successfully tested in the case of isotropic circles where the eigenvalues can be computed in terms of some equation involving the Bessel functions. The first eigenvalue can be used to get estimate on the index norm of the inclusion. The procedure has been validated in the scalar case (TM and TE modes) and for the case of full aperture. The perspective would be to test this in the case of limited aperture and for anisotropic 3-D cases.

6.7.4. Electrostatic imaging using conformal mappings

Participants: Yosra Boukari, Houssem Haddar.

In a series of recent papers Akduman, Haddar and Kress have developed a new simple and fast numerical scheme for solving two-dimensional inverse boundary value problems for the Laplace equation that model non-destructive testing and evaluation via electrostatic imaging. In the fashion of a decomposition method, the reconstruction of the boundary shape Γ_0 of a perfectly conducting or a nonconducting inclusion within a doubly connected conducting medium $D \subset \mathbb{R}^2$ from over-determined Cauchy data on the accessible exterior boundary Γ_1 is separated into a nonlinear well-posed problem and a linear ill-posed problem. The approach is based on a conformal map $\Psi : B \to D$ that takes an annulus B bounded by two concentric circles onto D. In the first step, in terms of the given Cauchy data on Γ_1, by successive approximations one has to solve a nonlocal and nonlinear ordinary differential equation for the boundary values $\Psi|_{C_1}$ of this mapping on the exterior boundary circle of B. Then in the second step a Cauchy problem for the holomorphic function Ψ in B has to be solved via a regularized Laurent expansion to obtain the unknown boundary $\Gamma_0 = \Psi(C_0)$ as the image of the interior boundary circle C_0.

In the present work, we are interested in the case where the solution satisfies an impedance boundary condition on Γ_0 (which can be seen as an approximation for a transmission problem between two conducting media). In that case the algorithm does not completely decompose the inverse problem into a well-posed nonlinear ordinary differential equation and an ill-posed Cauchy problem. Consequently its analysis and implementation is more involved and more than a straightforward extension of the algorithm for the Dirichlet or Neumann case. The first investigations by Haddar and Kress showed that when the impedance is relatively small the algorithm become unstable. We also noticed that instability is also linked with the size of the interior boundary.

In the present work we showed how the use of conjugate harmonics leads to a stabilization of the problem as in the case of the Neumann boundary conditions. The convergence analysis in the case of concentric circles show convergence for relatively small impedances. However it is not clear at the moment whether none of the algorithm can be convergent for a given setting of the problem or not.

6.7.5. Inverse scattering in waveguides

Participants: Laurent Bourgeois, Eric Lunéville.

We have investigated the reconstruction of scattering obstacles in waveguides via acoustic wave propagation. We have adapted the linear sampling method in such a context. The scattering data are obtained by generating waves from point sources in two typical situations

- the point sources describe one complete section S of the wave guide, assuming that the obstacle in located on one side of this section,
- the point sources describe two complete sections S and S' of the wave guide, that surround the obstacle.

The data for the inverse problem is the measurement of the acoustic field along S and/or S'.

We have reformulated this problem in terms of the amplitude coefficients of the scattered field on both propagative and evanescent modes of the waveguide. This is particularly helpful for developing the analog of the linear sampling method for the free space obstacle scattering problem.

From the numerical point of view, the main difference with the case of the free space is that, instead of the free space Green's fonction, we have to work with the Green's function of the wave guide which is easily expanded in terms of the guided modes. The numerical results (see figures) show that, in order to get a satisfactory reconstruction, it is sufficient and even necessary in practice to evaluate the projection of the measured field on the traces of propagative modes (although, in theory, evanescent modes are also needed).

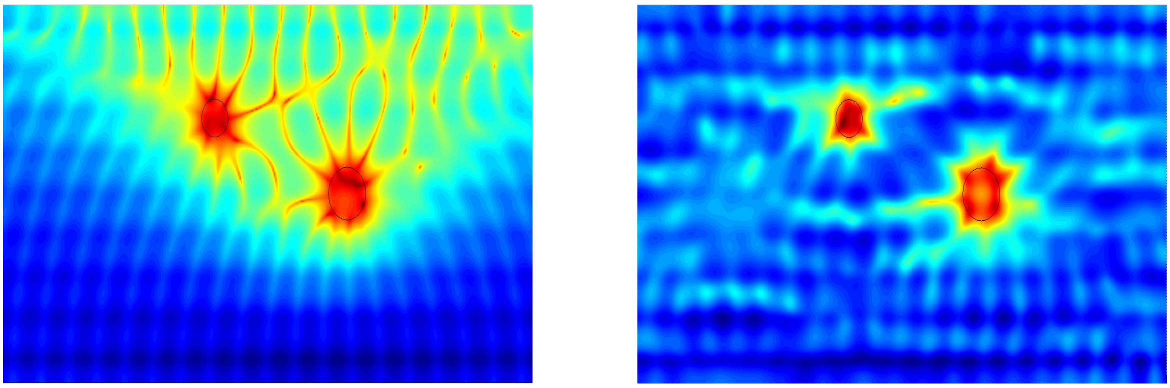

Figure 3. Reconstruction of obstacles in a waveguide. Exact (left) and noisy (right) data

6.7.6. Quasi-reversibility

Participants: Laurent Bourgeois, Jeremy Dardé, Eric Lunéville.

We have continued our works the method of quasi-reversibility to solve second order ill-posed Cauchy problems for an elliptic equation (as they appear in standard inverse problems).

For the numerical points of view, which constitute the subject of the PhD thesis of J. Dardé, our efforts have concerned the conforming approximation of the fourth-order problems introduced by the quasi-reversibility approach. As the usual Morley's element (based on second degree polynomials) does not lead to a sufficient accuracy, we are constructing improved Morley's elements that use third degree interpolation.

Concerning theoretical aspects, a study has been conducted concerning general stability results for ill-posed elliptic problem (which in particular lead to convergence rates for the method of quasi-reversibility), with the help of Carleman estimates. In particular, we extended some results previously obtained in infinitely smooth domains to $C^{1,1}$ class domains, as well as to domains with corners. These results were obtained by using global Carleman estimates, both interior and at the boundary, and are strongly related to the local regularity of the distance function to the boundary. We intend to study the intermediate situation of $C^{1,a}$ class domains (with $a <$ as well as the situation of general Lipschitz domains.

6.7.7. Time reversal

Participants: Christophe Hazard, Chokri Ben Amar.

This was the topic of the thesis of Chokri Ben Amar, who was defended this year. The novelty of the work was to extend the well kwnon time harmonic DORT theory (and corresponding numerical aspects) of M. Fink and his collaborators for non-intrusive time reversal mirrors to the case of intrusive mirrors : the mirrors are not only considered as source and receivers but interact with the scattered field (via boundary conditions or medium heterogeneities for instance), which is much more realistic from the point of view of applications. Moreover, the time dependent aspects of the theory have been investigated. We refer to the previous activity reports for more details about this subject.

6.7.8. Other topics

6.7.8.1. Fast solvers for evolution equations

Participant: Jing-Rebecca Li.

This is a work in collaboration with L. Greengard (Courant Institute). One principal area of research interest has been the solution of the heat equation, particularly in moving and/or unbounded domains. The challenge of problems posed on unbounded domains comes from the fact that using prevalent methods such as finite elements or finite difference methods, it can be difficult to couple the interior mesh to a high order discretization of transparent boundary conditions on an artificial boundary while maintaining stability. The challenge for discretizing moving boundaries is similar, namely the difficulty in obtaining high order and stable numerical schemes.

Our contribution to this research is the fast computation of the integral representation of the solution of the heat equation, which naturally takes into account the problem domain (possibly unbounded) and the boundary (possibly moving). For example, diffusion of heat into an infinite domain is automatically satisfied; there is no need for artificial boundary conditions. Similarly, a moving boundary means that one needs to compute integrals over this boundary and this can be done in a stable fashion. Our approach is suitable for the linear piece-wise constant coefficient heat equation, which occurs in numerous applications. The bottleneck of such an approach is the algorithmic complexity and memory requirements of computing time and spatial convolution integrals. This research focuses on accelerating both the time and spatial convolutions associated with the heat problem. The acceleration of the time convolution comes from computing the smooth part of the integral in the Fourier domain–coupling an efficient quadrature of the Fourier integral appropriate for unbounded domains with the Non-uniform FFT. We also developed an accurate quadrature for the non-smooth part of layer potential integrals–the goal being the treatment of domains whose geometrical properties may cause simpler time quadratures to suffer from slow convergence. The acceleration of spatial convolution is obtained by using the Fast Gauss Transform and other fast algorithms (still to be developed) treating the appropriate kernels. The resulting algorithm has $O(MN \log N)$ complexity, where N is the number of spatial discretization points and M the number of time steps, a significant improvement over the $O(M^2N^2)$ complexity of a naive implementation.

6.7.8.2. Modeling of dendritic solidification

Participant: Jing-Rebecca Li.

This is a work in collaboration with L. Brush (University of Washington) and D. Calhoun (CEA). The modeling of dendritic solidification is a perfect application for the fast heat equation solver we developed. We will take as an example a particular model for this physical process, called the phase field model.

The phase field model consists of a coupled system of two heat equations: the one governing the thermal field is linear and constant coefficient, the one governing the phase variable is nonlinear. Current methods use finite differences or finite elements to treat both equations. Difficulty occurs when one wants to simulate the solidification when the liquid is cooled to just slightly below its melting temperature. In this 'low undercooling' case, the solidification is slow. The solid-liquid interface moves slowly whereas the thermal field expands rapidly. In the absence of correctly formulated artificial boundary conditions, a finite differences/elements discretization of both equations is required to include in the computational domain the entire extent of the thermal field, which is much larger than the solidification front, the object of interest. For very low undercoolings, current methods based on finite differences/elements are not computational practical. A quote [from Braun and Murray, Journal of Crystal Growth, 1997] on adding adaptivity to simulate low undercoolings is illustrative of the potential difficulty: *Another issue that needs to be addressed in these types of simulations is the disparity between the dendrite size and the extent of the thermal field at small undercoolings. The larger domains and longer times allowed by adaptivity did not entirely solve this problem, and a more sophisticated mathematical approach for treating the domain boundary is required for computation at very small undercoolings.*

We believe our fast heat equation solver provides the sorely needed 'more sophisticated mathematical approach'. We have used the fast heat solver for the thermal field equation and coupled it to a finite difference method for the phase variable equation. In essence, the thermal field is allowed to correctly diffuse out of the computational domain, by construction. We then showed the feasibility of simulating the difficult case where the liquid experiences very low undercooling.

6.7.8.3. Control theory for parabolic equations

Participant: Jerome Le Rousseau.

We study more particularly the case of parabolic equations for which the diffusion coefficient in the principal part is discontinuous. In this case, only partial results have been obtained. The main tools in this work are Carleman estimates for elliptic and parabolic equations. These are fundamental estimates for the analysis of ill-posed Cauchy problems. They lead for instance to unique continuation properties. In the case of parabolic operators, these estimates allow to treat the controllability of some semi-linear equations. With such estimates, we have also been interested in the identification of coefficients for parabolic equations as inverse problems.

In the fall of 2007, in collaboration with L. Robbiano (Université de Versailles), we showed that the controllability of linear parabolic equations can be achieved without any restriction of the control location connected to the signs of the jumps of the diffusion coefficients. This questions had remained open since the work initiated by Doubova *et al.* (2002). To that purpose, we proved an interpolation inequality obtained from a local Carleman estimate for an associated elliptic operator. The proof is based on the separation of the problem in three microlocal regions. In some regions the classical techniques to prove Carleman estimates are used. In other regions, so-called Calderón-projector techniques are employed, which is fact yields an additional condition for the microlocalized solution at the interface. The partial estimates obtained in each microlocal region then yield the sought Carleman estimate, when combined together.

6.7.8.4. Linear elasticity

Participant: Patrick Ciarlet.

This is a joint work with Ph. Ciarlet (City University of Hong-Kong) and Jun Zou (Chinese University of Hong-Kong). We have shown that a classical elastostatic problem could be formulated as finding $\varepsilon \in \mathbf{E}$, the set of admissible square integrable symmetric tensors such that

$$J(\varepsilon) = \inf_{\mathbf{e}\in\mathbf{E}} J(\mathbf{e}), \quad J(\mathbf{e}) = \frac{1}{2}\int_\Omega \{\, \lambda\, \mathrm{tr}\mathbf{e} \cdot \mathbf{tr}\mathbf{e} + \mathbf{2}\mu\, \mathbf{e} : \mathbf{e}\,\}\, \mathbf{dx} - \Lambda(\mathbf{e}),$$

where (λ, μ) are the usual Lamé's parameters and Λ the linear form associated to the applied forces. We are invertigating two discretization approaches for solving numerically this minimisation problem

- The first one (the so-called Saint-Venant approach) consists in constructiong conforming finite element subspaces of $\mathbf{E}$,
- The first one (the so-called Donati approach) consists in treating the admissibilty conditions as equality constraints.

7. Contracts and Grants with Industry

7.1. Contract POEMS-DGA

Participants: Patrick Ciarlet, Grace Hechme.

This contract concerns the Singular Expansion method for time dependent problems and the resolution of transient Maxwell's equations in singular domains.

7.2. Contract POEMS-EADS-1

Participants: Sonia Fliss, Patrick Joly.

This contract is about the numerical simulation of elastic wave propagation in composite materials (periodic structures with a defect) in the time harmonic regime.

7.3. Contract POEMS-EADS-2

Participants: Anne-Sophie Bonnet-Ben Dhia, Eve-Marie Duclairoir, Jean-François Mercier.

This contract is about the numerical simulation of frequency domain aeroacoustics using Galbrun's equations and regularized finite element techniques.

7.4. Contract POEMS-Airbus

Participants: Patrick Joly, Jeronimo Rodríguez.

This contract is about the hybridation of time domain numerical techniques in aeroacoustics (Linearized Euler equations).

7.5. Contract POEMS-ONERA-CE Gramat

Participants: Gary Cohen, Patrick Joly.

This contract is about hybrid methods for the time domain solution of Maxwell's equations.

8. Other Grants and Activities

8.1. National Cooperations

- SimNanoPhot : project of the ANR in collaboration with IEF (Institut d'Electronique Fondamentale) of the University of Orsay. It concerns the modelization of micro and nano-structures in optics.
- GDR Ultrasons: this GDR, which regroups more than regroup 15 academoc and industrial research laboratories in Acoustics and Applied Mathematics working on nondestructive testing. It has been renoveled this year with the participation of Great Britain.
- ANR (RNTL) project *MOHYCAN: MOdélisation HYbride et Couplage semi-ANalytique pour la simulation du CND*.
  Topic: *On the coupling of the finite element code ATHENA with the semi-analitic code CIVA. Non-destructif testing.* Collaborators: CEA-LIST (main contact), EDF and CEDRAT.

8.2. International Cooperations

- The project is involved in the INRIA/NSF collaboration "Collaborative Effort on Approximate Boundary Conditions For Computational Wave Problems" with J. Hesthaven (Brown University) and P. Petropoulos (New Jersey University).
- The Project is involved in a STIC project with the LAMSIN of ENIT (Tunis) with A. Ben Abda and N. Gmati.
- The Project is member of the Associate Team ENEE between INRIA and Maghreb.
- The GDR Ultrasons has been extended to a collaboration with United Kingdom.

8.3. Visiting researchers

- Ibrahim Akudman, Professor at Istambul Technical University,
- Marteen de Hoop, Professor at Purdue University,
- Rainer Kress, Professor at the University of Göttingen,
- Paul Martin, Professoor at Colorado School of Mines, was visiting us in May and June,
- Andrès Prieto, University of Santiago de Compostela,
- Vladimir Tcheverda, Russian Academy of Sciences.

9. Dissemination

9.1. Various academic responsibilities

- A. S. Bonnet-Ben Dhia is the Head of the Electromagnetism Group at CERFACS (Toulouse)
- A. S. Bonnet-Ben Dhia is in charge of the relations between l'ENSTA and the Master "Dynamique des Structures et des Systèmes Couplés (Responsible : Etienne Balmes)".
- P. Joly is a member of the Commission de Spécialistes of the University Paris VII.
- P. Joly is a member of the Hiring Committee of Ecole polytechnique in Applied Mathematics.
- P. Joly is a member of the Post Docs Commission of INRIA Rocquencourt.
- P. Joly is a member of the Scientific Committee of the Seminar in Applied Mathematics of College de France (P. L. Lions).
- P. Joly is a member of the Book Series Scientific Computing of Springer Verlag.

- P. Joly is an expert for the MRIS (Mission pour l'Innovation et la Recherche Scientifique) of DGA (Direction Générale de l'Armement)
- P. Joly was co-organizer (with R. Hiptmair, R. Hoppe and U. Langer) of the workshop on *Computational Acoustics and Electromagnetism* at Oberwolfach (February)
- P. Joly was co-chairman (with S. Chandler-Wilde) of the International Conference WAVES2007 (July, Reading, England)
- M. Lenoir is a member of the Commission de Spécialistes of CNAM.
- J. Le Rousseau is coordinator of the CoNum project, "Numerical control, application to biology", Projet ANR JeuneS chercheurs.
- J. Le Rousseau has co-organized (with M. de Hoop and G. Uhlmann) the conference "Microlocal Analysis, Harmonic Analysis and Inverse Problems" at CIRM, Marseille (March 2007)
- J. Le Rousseau is elected member of CNU (26ème section)
- J. R. Li is one of the guest editors of the special issue of the Journal of Computational mathematics that will follow the WAVES2007 Conference.
- E. Lunéville is the Head of UMA (Unité de Mathématiques Appliquées) at ENSTA.
- Several members of the Project have been involved in the organization of the WAVES2007 Conference.
- The Project organizes the monthly Seminar Poems (Coordinators: X. Claeys, J. F. Mercier)

9.2. Teaching

- Eliane Bécache
  - *Introduction à la théorie et l'approximation de l'équation des ondes*, 3eme année à l'ENSTA (Paris) et Master 2 UVSQ
- Laurent Bourgeois
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA, Paris
  - *Contrôle optimal des EDP*, ENSTA, Paris
- Anne-Sophie Bonnet-Ben Dhia
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA, Paris
  - *Propagation d'ondes*, Master de Dynamique des Structures et Couplages, Ecole Centrale de Paris
  - *Guides acoustiques*, Master de Dynamique des Structures et Couplages, Ecole Centrale de Paris
  - *Théorie spectrale des opérateurs autoadjoints et application aux guides optiques*, ENSTA, Paris
- Xavier Claeys
  - *Bases d'Analyse et Algèbre*, UVSQ, Versailles
  - *Méthode des éléments finis*, ENSTA, Paris
- Gary Cohen
  - *Cours de Master II: Méthodes numériques pour les équations des ondes*, Université de Paris-Dauphine October-December 2006
- Bérangère Delourme
  - *Algèbre linéaire*, Université Paris IX

- Sonia Fliss
  - *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA, Paris
  - *Introduction à MATLAB*, ENSTA, Paris
  - *Fonctions de la variable complexe*, ENSTA, Paris
- Houssem Haddar
  - *Calcul Scientifique*, Ecole des Mines, Paris
  - *Cours Eléments Finis*, ENSTA, Paris
  - *Problèmes directs et inverses en théorie de la diffraction*, Master 2 Paris 6, Parcours Analyse Numérique et EDP
- Christophe Hazard
  - *Théorie Spectrale et application aux guides optiques*, ENSTA, Paris.
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA, Paris.
- Patrick Joly
  - *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA, Paris
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA, Paris
  - *Problèmes directs et inverses en théorie de la diffraction*, Master 2 Paris 6, Parcours Analyse Numérique et EDP
- Lauris Joubert
  - *Fonctions d'une variable complexe*, ENSTA, Paris
- Marc Lenoir
  - *Fonctions d'une variable complexe*, ENSTA, Paris
  - *Méthodes d'équations intégrales*, ENSTA, Paris
- Jing-Rebecca Li
  - *Introduction a la discretisation des EDPs*, ENSTA, Paris
  - *Calcul Scientifique*, Ecole des Mines, Paris
- Eric Lunéville
  - *Introduction à MATLAB*, ENSTA, Paris
  - *Contrôle optimal des EDP*, ENSTA, Paris
- Jean-François Mercier
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA, Paris
  - *Fluides incompressibles*, ENSTA, Paris
  - *Fonctions de la variable complexe*, ENSTA, Paris
  - *Ondes dans les milieux continus*, ENSTA, Paris
- Jeronimo Rodríguez
  - *Optimisation quadratique*, ENSTA, Paris
  - *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA, Paris
  - *Introduction à la simulation numérique*, ENSTA, Paris
- Adrien Semin

  - Monitorat, University of Versailles-Saint Quentin.
- Carlo Maria Zwölf
  - Monitorat, University of Versailles-Saint Quentin.

9.3. Participation in Conferences, Workshops and Seminars

- Vahan Baronian
  - *Transparent boundary conditions for the harmonic diffraction problem in an elastic waveguide*, WAVES2007, Reading (England), July 2007
- Anne Sophie Bonnet-Ben Dhia
  - *Le traitement des frontières artificielles en simulation des ondes : le cas des guides d'ondes en régime périodique établi*, Convergences mathématiques franco-maghrébines, Nice, January 2007
  - *Time-harmonic wave transmission problems with sign-shifting material coefficients*, WAVES2007, Reading (England), July 2007
- Laurent Bourgeois
  - *Sur la discrétisation de la méthode de quasi-reversibilité pour la résolution de problèmes elliptiques mal posés*, Séminaire á l'Université de Metz, March 2007
  - *The method of quasi-reversibility to solve the Cauchy problem for elliptic PDE*, Conference ICIAM 2007, ETH, Zürich (Suisse), July 2007
- Patrick Ciarlet
  - Séminaire à l'Université de Zürich (Zürich, Suisse), January 2007
- Xavier Claeys
  - *A generalized Holland model for wave diffraction by thin wires*, WONAPDE, Concepcion (Chili), January 2007
  - *A generalized Holland model for wave diffraction by thin wires*, Workshop "*Computational Acoustics and Electromagnetism*", Oberwolfach (Germany), February 2007
  - *A generalized Holland model for wave diffraction by thin wires*, Cinquiemes journees singulieres, CIRM, Luminy, France, April 2007
  - *Theoretical justification of Pocklington's equation for diffractionby thin wires*, WAVES2007, Reading (England), July 2007
  - *A generalized Holland model for wave diffraction by thin wires* International Conference on Electromagnetics in Advanced Applications, ICEAA, Torino, Italy, September 2007
  - *Justification mathématique du modèle de Pocklington pour la diffraction d'une onde électromagnétique par un fil mince*, Séminaire à l' Université de Valenciennes, October 2007
  - *Theoretical justification of Pocklington's equation for diffractionby thin wires*, Journée sur les Techniques Asymptotiques en Electromagnétisme, CERFACS (Toulouse), October 2007
  - *Justification mathématique du modèle de Pocklington pour la diffraction d'une onde électromagnétique par un fil mince*, Séminaire à l' Université de Rennes I, November 2007
  - *Justification mathématique du modèle de Pocklington pour la diffraction d'une onde électromagnétique par un fil mince*, Séminaire à l' Université de Clermont-Ferrand, December 2007

- M. Duruflé
  - *Efficient Resolution of 3-D Maxwell's Equations in Frequency Domain, with Higher-Order Finite Element Methods*, WAVES2007, Reading (England), July 2007
  - *Modes parasites pour les éléments finis d'ordre élevé appliqués aux équations de Maxwell en régime harmonique*, Séminaire à l'université de Cergy-Pontoise, February 2007
  - *Numerical integration and high-order finite element methods applied to Maxwell equations* Seminaire at Sandia National Laboratories, May 2007
- Sonia Fliss
  - *Wave propagation in locally perturbed periodic media*, WONAPDE, Concepcion (Chili), January 2007
  - *Computation of harmonic wave propagation in infinite periodic media*, Workshop "*Computational Acoustics and Electromagnetism*", Oberwolfach (Germany), February 2007
  - *Exact boundary conditions for locally perturbed 2d-periodic plane*, WAVES2007, Reading (England), July 2007
  - *Transparent boundary conditions for wave propagation locally perturbed 2d-periodic media* Premier Workshop sur "Méthodes pour les problèmes direct et inverse de diffraction : progrès récents", Pau (France), December 2007
- Houssem Haddar
  - Invited speaker to the *International Workshop on Integral Equations and Shape Reconstruction*, on the occasion of Prof. Dr. Kress 65th birthday, Goettingen, January 2007.
  - Invited speaker to the Oberwolfach workshop, *Inverse Problems in Wave Scattering*, Oberwolfach, March 4-10, 2007.
  - Invited for a short visit to the Electromagnetic Research Group, Istanbul Technical University, November 2007.
  - *Efficient Numerical Solutions of Large Multi-dimensional Inverse Scattering Problems*, Aces'07 conference (Mini-symposium), March 2007.
  - *High-order methods for computational wave propagation and scattering*, AIM workshop (invited speaker) Palo Alto, September 2007.
  - Invited speaker in the workshop *Méthodes pour les problèmes direct et inverse de diffraction : progrès récents*, Université de Pau et des Pays de l'Adour, December 2007.
- Patrick Joly
  - *Higher order time discretization wth optimal CFL conditions for second order hyperbolic problems*, WONAPDE (invited speaker), Concepcion (Chili), January 2007
  - *Analyse de la stabilité d'un modèle pour la propagation d'ondes dans un tuyau de faible épaisseur parcouru par un fluide en écoulement*, Conference TAMTAM'07 (plenary speaker), Tipaza (Algérie), April 2007
  - *Higher order explicit time stepping and optimal CFL condition for second order hyperbolic problems*, WAVES2007, Reading (England), July 2007
  - *Conservative local time stepping for the approximation of symmetric hyperbolic systems by discontinuous Galerkin methods*, WAVES2007, Reading (England), July 2007
  - *Transparent boundary conditions, wave propagation and periodic media*, Conferencier ENUMATH07 (plenary speaker), Graz (Autriche), Septembre 2007
  - *Modèles approchés pour la propagation d'ondes dans un réseau de fentes minces*, Journée sur les Techniques Asymptotiques en Electromagnétisme, CERFACS (Toulouse), October 2007

   - *Transparent boundary conditions, wave propagation and periodic media*, Seminar at Laboratoire de Mécanique et Acoustique (LMA), Marseille, France. December 2007

- Jing-Rebecca Li
   - *Fast and accurate computation of layer heat potentials*, Conference ICIAM 2007, ETH, Zürich (Suisse), July 2007
   - Seminar at Courant Institute, New York University, September 2007.
   - Seminar at Columbia University, Applied Math, September 2007.
   - Seminar at Dartmouth College, Dept. of Math, September 2007.
   - Seminar at University of Michigan, Dept. of Math, September 2007.

- Jérome Le Rousseau
   - *Controllability of parabolic equations with non-smooth coefficients by means of global Carleman estimates*, seminar at Tokyo National University, Japan, January 2007.
   - *Controllability of parabolic linear and semilinear equations: null controllability results and recent progress in the case of non-smooth coefficients*: Université de Tsukuba, Japan, January 2007.
   - *FIO-product representation of solutions to symmetrizable hyperbolic systems*, Conference "Spectral and scattering theory and related topics" (invited), Research Institute of Mathematical Sciences (RIMS), February 2007
   - *FIO-product representation of solutions to hyperbolic equations, applications to seismic imaging*, Workshop on inverse problems (invited), Université de Tsukuba, Japan, April 2007
   - *FIO-product representation of solutions to symmetrizable hyperbolic systems*, Conference ICIAM 2007 (invited in a minisymposium), ETH, Zürich (Suisse), July 2007
   - *On the controllability on parabolic PDEs with non-smooth coefficients*, Symposium "Control and Optimization of Nonlinear Evolutionary PDE Systems", 23rd IFIP TC 7 Conference on System Modelling and Optimization, Cracovie, Pologne, July 2007.
   - *On the controllability on parabolic PDEs with non-smooth coefficients*, Workshop on Analysis and Control of Partial Differential Equations (ANCPDE07), Pont-à-Mousson, France, June 2007
   - Workshop on control and inverse problems, Besançon, France, 26–27 septembre 2007
   - *Sur les produits d'opérateurs intégraux de Fourier* Séminaire LAGA, Université Paris-Nord, 9 mars 2007
   - *Contrôlabilité des EDP paraboliques à coefficients discontinus* Séminaire EDP, Institut Elie Cartan, Nancy, October 2007
   - *Sur les produits d'opérateurs intégraux de Fourier* Séminaire d'analyse appliquée, LAMFA, Université de Picardie, Amiens, October 2007
   - *Sur les produits d'opérateurs intégraux de Fourier* Séminaire du Laboratoire de Mathématiques Raphaël Salem (LMRS), Université de Rouen, October 2007

- Eric Lunéville
   - *Finite element simulation of time-harmonic aeroacoustics with a generalized impedance boundary condition*, 13th AIAA/CEAS Aeroacoustics Conference , Roma (Italy), May 2007

- Jean-François Mercier

  - *A low Mach model for time harmonic acoustics in arbitrary flows*, WAVES2007, Reading (England), July 2007
  - *Finite element simulation of time-harmonic aeroacoustics in a shear flow*, 13th AIAA/CEAS Aeroacoustics Conference , Roma (Italy), May 2007
- Jeronimo Rodríguez
  - *El método de bases reducidas aplicado a problemas de propagación de ondas en régimen armónico*, Seminar at the University of Santiago de Compostela, Spain, April 2007
  - *La méthode de bases réduites pour des problèmes de propagation d'ondes en régime harmonique*, Séminaire GTN. Université de Cergy-Pontoise, France, April 2007
  - *Présentation et analyse des méthodes de raffinement de maillage espace-temps conservatives pour des problèmes de propagation d'ondes*, 8eme Colloque en Calcul des Structures. Giens, France, May 2007
  - *Certified DG-FEM Reduced Basis Methods and Output Bounds for the Harmonic Maxwell's Equations*, International Workshop on High-Order Finite Element Methods (HOFEM). Herrsching, Germany, May 2007
  - *Conservative methods for the discretization of wave propagation problems with local time stepping.* Seminar POEMS, École Nationale Supérieure de Techniques Avancées, Paris, France. May 11th 2006.
  - *Space-time mesh refinement methods for elastodynamics.* GDR 2501. Presqu'île de Giens. France. May 14th 2006 – May 19th 2006.
  - *Reduced basis method for harmonic wave propagation problems.* Seminar at Laboratoire de Mécanique et Acoustique (LMA), Marseille, France. November 21st 2006.
  - *Reduced basis output bounds for harmonic wave propagation problems.* CEA-EDF-INRIA School on Discontinuous Galerkin Methods, INRIA Rocquencourt, France. November 27th 2006 – December 1st 2006.
- A. Semin
  - *Analyse asymptotique de la propagation d'ondes dans des jonctions de fentes minces*, Séminaire, Université Paul Sabatier, Toulouse, France, September 2007
  - *Étude de la propagation d'ondes dans des jonctions de fentes minces*, Séminaire ACSIOM, Université Montpellier II, France, November 2007

10. Bibliography

Year Publications

Books and Monographs

[1] P. JOLY. *Numerical Methods for Elastic Wave Propagation*, CISM Course and Lectures, vol. 495, SpringerWien New York, 2007.

Doctoral dissertations and Habilitation theses

[2] C. BEN AMAR. *Etude théorique et numérique de processus de retournement temporel*, Ph. D. Thesis, 2007.

[3] E.-M. DUCLAIROIR. *Rayonnement acoustique dans un écoulement cisaillé : Une méthode d'éléments finis pour la simulation du régime harmonique*, Ph. D. Thesis, March 2007.

[4] S. KADDOURI. *Résolution du problème du potentiel électrostatique dans des domaines prismatiques et axisymétriques singuliers. Etude asymptotique dans des domaines quasi-singuliers*, Ph. D. Thesis, March 2007.

[5] J. LE ROUSSEAU. *Représentation Microlocale de Solutions de Systèmes Hyperboliques, Application à l'Imagerie, et Contributions au Contrôle et aux Problèmes Inverses pour des Équations Paraboliques*, Ph. D. Thesis, November 2007.

Articles in refereed journals and book chapters

[6] R. BARTHELMÉ, P. CIARLET, E. SONNENDRÜCKER. *Generalized formulations of Maxwell's equations for numerical Vlasov-Maxwell simulations*, in "Math. Models Meth. App. Sci.", vol. 17, 2007, p. 657–680.

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[8] A. BENABDALLAH, Y. DERMENJIAN, J. LE ROUSSEAU. *Carleman estimates for the one-dimensional heat equation with a discontinuous coefficient and applications to controllability and an inverse problem*, in "J. Math. Anal. Appl.", vol. 336 (2), 2007, p. 865–887.

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[10] A. BENABDALLAH, P. GAITAN, J. LE ROUSSEAU. *Stability of discontinuous diffusion coefficients and initial conditions in an inverse problem for the heat equation*, in "SIAM J. Control Optim.", 2007.

[11] A.-S. BONNET-BENDHIA, P. CIARLET, C. M. ZWÖLF. *Two-field and three-field formulations for wave transmission between media with opposite sign dielectric constants*, in "Journal of Computational and Applied Mathematics", vol. 204, 2007, p. 408–417.

[12] A.-S. BONNET-BENDHIA, E.-M. DUCLAIROIR, G. LEGENDRE, J.-F. MERCIER. *Time-harmonic acoustic propagation in the presence of a shear flow*, in "J. Comput. Appl. Math", vol. 204(2), 2007, p. 428–439.

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