INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team POEMS

Wave propagation: Mathematical Analysis and Simulation

Rocquencourt

THEME NUM

Activity Report

2005

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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, three 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,
- 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 imstruments, 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.

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, and design of optoelectronic micro-components.

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,...
- We have been participating since 2002, to the ARC HEADEXP concerning the simulation of electromagnetic waves in the brain.
- 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.

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) 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

- **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, ...).

- **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.

5.2. Prototype software

- **ACOUS2D :** This software was written in the frame of S. Fauqueux's thesis. Property of INRIA. It concerns the simulation of transient acoustic waves in an a 2D inhomogeneous medium based on a mixed formulation of spectral elements. Sources are spherical and reflecting boundaries can be of Dirichlet or Neumann types and unbounded domains are taken into account by using PML.
- **ELASTIC2D :** Same characteristics and author as ACOUS2D for transient linear elastodynamic waves. The media can also be anisotropic. Property of IFP, INRIA owns a copy for research purposes.
- **ELASTIC3D :** Same as ELASTIC2D in 3D.
- **RAPH-ELAS :** This code, developed by J. Rodriguez, is devoted to solve the linear elastodynamic equations in 2D. This solver, that is based on ELAST-2D (developed by C. Tsogka), includes the possibility of doing recursive local space-time mesh refinement of arbitrary ratio. RAPH-ELAS will be included in ATHENA-2D, the code of the electricity company EDF.
- **Contact2D :** This code, developed on the basis of ELAST-2D by G. Scarella, solves 2D elastodynamics equations in heterogeneous media in the presence of cracks modeled with pure unilateral contact conditions. It has been implemented as a part of the code ATHENA-2D (EDF).
- **VISCO2D :** This code, written by A. Ezziani in the framework of collaborations with IFREMER and SHELL , is an extension of the mixed finite element code ELAST-2D of C. Tsogka to viscoelastic media (generalized Zener's models). sold to SHELL.
- **APE2D :** This has been written by A. Ezziani in the framework of a contract with SHELL. It concerns the simulation of waves in poro-elastic media (Biot's model) by higher order finite elements with mass lumping and PML's for open boundaries.

- **FLUID-STRUCT2D :** This software was written in the frame of S. Fauqueux's thesis during a 6 weeks stay at Caltech. Property of IFP, INRIA owns a copy for research purposes. It models the propagation of a transient acoustic wave in a solid through a fluid in 2D. Its purpose is the modeling of acoustic waves in the sea for seismic prospection. The numerical models in fluid ans solid are the same as those used in ACOUS2D and ELASTIC2D.
- **Flusol2d :** This, developped by J. Diaz on the basis of ELAST-2D, is aimed at solving fluid-structure interaction problem in the case of a plane interface in two dimensions. It is based on a mixed dual-dual formulation : a variational formulation where the pressure in the fluid and the velocities in the solid are searched in an L^2-like space and the velocities in the fluid and the stresses in the solid are searched in an $H(div)$ like space. This code is used by IFREMER.
- **Flusol3d :** This software solves fluid-structure interaction problems in three dimensions in general geometries . It is based on a primal-primal formulation (a variational formulation where the pressure in the fluid and the velocities in the solid are searched in an $H^1 - like$ space and the stresses in the solid are searched in an $L^2 - like$ space) and spectral finite elements.
- **MAXANIR :** Modeling transient TM Maxwell's equations by a mixed edge element method on hexahedric meshes with mass-lumping. The media can be inhomogeneous and anisotropic. Sources can be spherical or plane waves, reflecting boundaries are metallic and unbounded domains are taken into account by using PML. This software was written by G. Cohen. Property of INRIA.
- **MAXWELL2D :** Modeling transient TE or TM Maxwell's equations rewritten in a wave equation formalism, which enables to use mixed spectral elements instead of edge elements. The media can be inhomogeneous and anisotropic. Sources can be spherical or plane waves, reflecting boundaries are metallic and unbounded domains are taken into account by using PML. This software was written by S. Fauqueux in the frame of a start-up incubation. Property of INRIA.
- **MAX2D :** This code, written by P. Ciarlet and E. Jamelot, solves time dependent 2D Maxwell's equations in singular domains, using Lagrange finite elements and particular treatments of singularities.
- **MAXTETRA3D :** This code has been developed by C. Poirier, H. Haddar and S. Vérité. The object is the resolution 3D time domain Maxwell's equations using tetrahedric second order edge elements with mass lumping. It uses the automatic 3D mesh generator NetGen developed by A. Schröbel. This code has been used for the ARC HEADEXP.
- **GeDeOND :** Modeling transient 3D Maxwell's equations by a discontinuous Galerkin method on hexahedric meshes. The media can be inhomogeneous and anisotropic. Sources can be spherical or plane waves, reflecting boundaries are metallic and unbounded domains are taken into account by using PML. This software was written in the frame of S. Pernet's thesis at ONERA-Toulouse. Property of INRIA and ONERA.
- **MONTJOIE :** This code has been written by M. Duruflé in the framework of a collaboration with ONERA. It concerms the resolution, by volumic methods, of the Helmholtz equation and the time-harmonic Maxwell's equations, both in 2-D and 3-D. This code uses spectral finite element method on quadrilateral/hexahedral meshes for the scalar case. It uses finite edge element for the vectorial case.
- **MODALOPT :** This code, written by E. Lunéville, based on multi-modal decomposition of waveguides of variable cross-section, is able to solve inverse problems (by minimization techniques) such as shape optimization or shape identification.

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. Mixed spectral finite element methods for vibroacoustics

Participants: Gary Cohen, Pascal Grob, Arnaud Kelbert.

The works in this direction have been devoted to fluid-structure interaction problems arising in vibroacoustics (vibations and sound radiation of a plate). This is the subject of the PhD thesis of P. Grob, boursier CIFRE with EADS). He has studied a method based on coupling 2D (for the plate) and 3D (for the fluid) mixed spectral elements of different orders. Theoretical aspects of the numerical model were studied and error estimates were derived. Numerical validations were made.

During his stage, Arnaud Kelbert (INSA Rouen) has worked on the extension of spectral elements to thin shells.

6.2.2. Discontinuous Galerkin Methods in Aeroacoustics

Participants: Gary Cohen, Nicolas Castel.

We are studying a high order discontinuous Galerkin method using quadrilateral meshes and quadrature formulae on Gauss points for linearized Euler equations. The results for aeroacoustic test cases were presented in Waves'05, at a summer CEMRACS in Marseille in July 2005 and in Angers, in October 2005 (Journee d'etude sur la propagation acoustique en ecoulement). The numerical method used allows us to use different orders of polynomial approximation in different areas. Combining this with local time-stepping should be the next step of this research.

6.2.3. Space-Time mesh refinement for Discontinuous Galerkin Methods

Participants: Abdelaâziz Ezziani, Patrick Joly.

This new thematic is developed via the post-Doc of A. Ezziani in collaboration with Airbus. The general framework of this collaboration is the hybridization of numerical domains for the time-domain solution of Linearized Euler equations in aeroacoustics.
We have been interested in non conforming space-time mesh refinement methods for wave propagation in aeroacoustics, in the spirit of previous work in electromagnetism and elastodynamics. We have developed a method which is appplicable to zero order perturbations of symmetric hyperbolic systems in the sense of Friedrichs (Linearized Euler equations are of this type). The method is based on the one hand on the use of a conservative higher order discontinuous Galerkin approximation for space discretization and a finite difference scheme in time, on the other hand on appropriate discrete transmission conditions between the grids. We use a discrete energy techniques to drive the construction of the matching procedure between the grids and guarantee the stability condition. Moreover, under suitable geometrical conditions on the grids, this method is fully explicit.

6.2.4. Regularized finite element method for Galbrun's equations

Participants: Kamel Berriri, Anne-Sophie Bonnet-Ben Dhia, Patrick Joly.

This is the continuation of the PhD thesis of K. Berriri on Galbrun's equations for time dependent aeroacoustics. We have proposed a regularization method which allows the use of Lagrange finite elements in a stable manner. The numerical results illustrate the interest of the regularization.
Furthermore, we have been interested in the design of the absorbing boundary conditions, which has led us to tackle some new difficulties related to the regularization process.

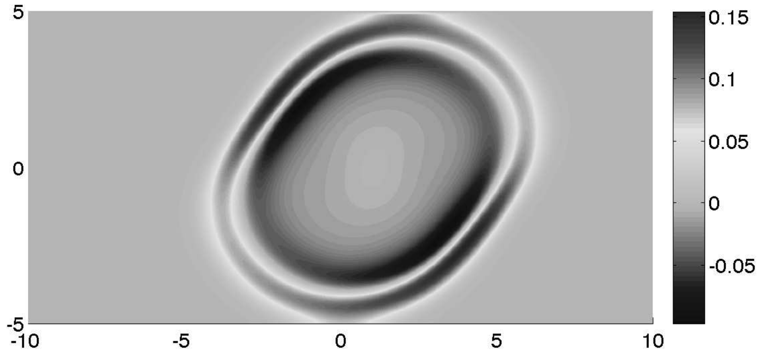


Figure 1. Acoustic pressure field in a shear flow

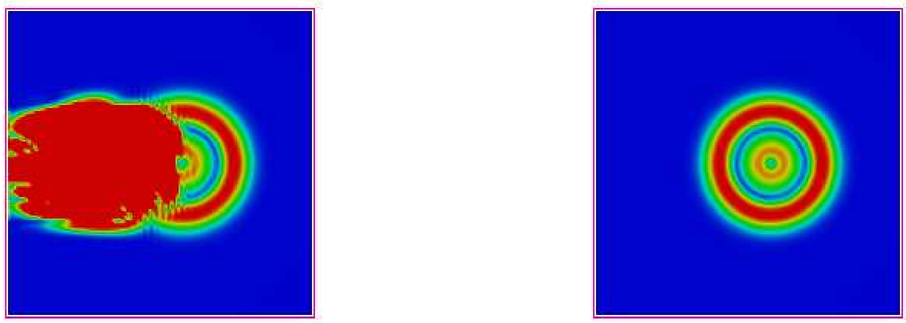


Figure 2. Numerical solution at the same time for the non-regularized problem (at the left) and the regularized problem (at the right)

6.2.5. Combining integral equations and finite elements in vibroacoustics

Participants: Pascal Grob, Patrick Joly.

We are interested in the acoustic radiation of the vibrations of a thin mechanical structure (typically a plate). This is done in collaboration with EADS.
We have developed an original method based on the coupling between spectral finite elements for the mechanical part of the problem and retarded potentials for the acoustic part. The stability theory is now complete and the first numerical experiments have permitted us to validate the method.

6.2.6. Modeling of Structural noise in non destructive testing

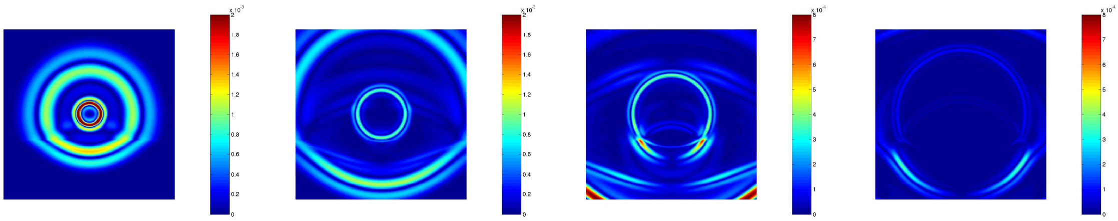
Participant: Julien Diaz.

This is the subject of the Post-Doc of J. Diaz, in collaboration with EDF.
We are here interested in crack detection in weld by ultrasonic waves in 2D. In a first approximation, those welds can be described by piecewise homogeneous elastic media, with an anisotropy constant in each domain. Actually, each domain is not rigorously homogenous but composed of numerous discrete grains whose crystallographic axes are differently oriented. One of the axes is the same in each grain, but the remaining axes are randomly oriented. The lengths and the widths of the grains also follow a random law. This heterogeneity induces the so-called structural noise. As a consequence the theory predicts that a wave propagating in such a medium is attenuated when compared to the one propagating in an homogeneous medium.
Even if the problem can still be regarded as a 2D problem, one then needs a 3D description of the elastodynamic tensor of each grain. We then have had to adapt our elastodynamic code (Athena2D) in order to take into account this description. More over, welds are modeled as random media. Our goal is to understand the influence of the parameters (length, width and orientation of the grains) on the attenuation of the waves through numerical experiments and to confront our results to the theory.

6.2.7. A Higher order mixed finite element method for wave propagation in poroelastic media

Participants: Eliane Bécache, Abdelaâziz Ezziani, Patrick Joly.

In this work, we are interested in the mathematical and numerical modeling of wave propagation in poroelastic media. We consider the Biot's model, for which we achieve a mathematical analysis, in particular, an existence and uniqueness of solution and an energy decay result. For the numerical resolution, we construct a method based on a higher order mixed finite element approximation in space and a finite difference scheme in time. We prove for the scheme obtained a result of discrete energy decay which provides a sufficient stability condition. To simulate the propagation in unbounded domains, we use the perfectly matched layers techniques (see figure 3 for some numerical validations).



(a) $t = 0.055$ s (b) $t = 0.085$ s (c) $t = 0.12$ s (d) $t = 0.18$ s

Figure 3. Velocity in an heterogeneous unbounded poroelastic medium

6.2.8. Treatment of singularities in electromagnetism

Participants: Patrick Ciarlet, Erell Jamelot.

This is the subject of the PhD thesis of E. Jamelot, which has been defended in December 2005.
Two methods have been studied and implemented to solve the static and the time-dependent (instationary) Maxwell equations in a homogeneous media, around a perfectly conducting body, with a non-smooth interface. These two methods are:

- the Singular Complement Method, which works for 2D and 2D-1/2 geometries;
- the Weighted Regularization Method, which works for 2D and 3D geometries.

Both methods allow to capture accurately the singular behavior of the electromagnetic field near the geometrical singularities of the interface.

6.2.9. The Singularity Expansion Method

Participants: Christophe Hazard, François Loret.

The recent works concern the analysis of the quality of the approximation given by the Singularity Expansion Method. The numerical results show that the approximation becomes correct when the wavefront of the incident wave has passed the obstacle, but its quality depends on the frequency content of this incident wave (an analysis of the error by Prony's method is in progress).

6.2.10. Fast solvers for evolution equations

Participant: Jing Li.

This work is developed in collaboration with L. Greengard (Courant Institute). This year we have worked on the fast solution of the heat equation: the idea os to compute the solution from integral representation by time-stepping in Fourier space and using Non-uniform FFT.

6.3. Time-harmonic diffraction problems

6.3.1. Aeroacoustics

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

The numerical method, combining a regularized formulation of Galbrun's equations and Perfectly Matched Layers, already used to compute the aeroacoustic radiation of a source in a duct for a uniform flow, has been extended to the case of shear flows. The effect of the continuum of hydrodynamic modes clearly appears in the numerical results (cf. figures).

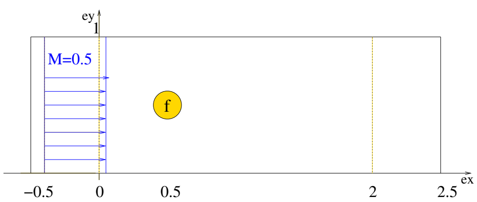


Figure 4.

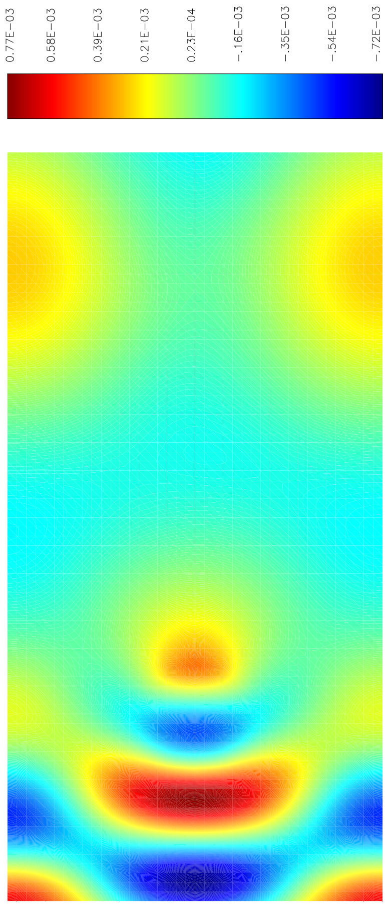


Figure 5. Acoustic wave propagation in a uniform flow

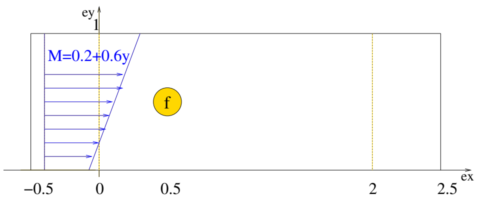


Figure 6.

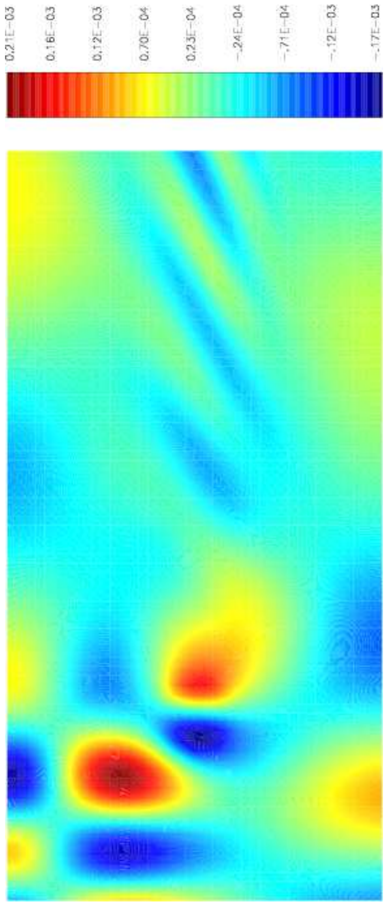


Figure 7. Acoustic wave propagation in a shear flow

6.3.2. Modeling of meta-materials in electromagnetism.

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

Carlo Maria Zwölf (PhD student) has been working in this field since the end of 2004, under the joint supervision of Anne-Sophie Bonnet-Ben Dhia and Patrick Ciarlet. We consider a simplified scalar model problem related to Maxwell's equations, involving wave transmission between media with opposite sign dielectric and/or magnetic constants. We build two variational formulations equivalent to the model problem. Under some suitable conditions, both formulations are well-posed since they fit into the coercive plus compact framework. Advantages over previous studies is the validity of the formulations in the general case of Lipschitz interface between the two media and L^∞ dielectric and magnetic constants. An interesting feature of these formulations is that they allow a simple finite element numerical implementation.

6.3.3. Time harmonic Maxwell's equations

Participants: Gary Cohen, Marc Duruflé.

This is the subject of the PhD thesis of M Duruflé, in the framework of a collaboration with ONERA. It will be defended in February 2006.
This year, we have studied high-order finite edge-elements for the discretization of time-harmonic Maxwell's equations in axisymmetric domains. This approach is coupled with a high-order approximation of an exact boundary integral equation, in order to take in account the Sommerfeld radiation condition. The numerical results we have obtained show how interesting it can be to use high-order finite elements for Helmholtz equations and Maxwell equations in 3-D cases.

6.3.4. Diffraction problems in locally perturbed periodic media

Participants: Sonia Fliss, Patrick Joly, Jing Li.

We are interested in the numerical simulation of the propagation of waves in locally perturbed periodic media. Natural applications occur in electromagnetism (photonic crystals) or mechanics (non destructive testing in composite materials, a subject developed in collaboration with EADS)

We have elaborated a method for the reduction of the effective numerical calculations to the neighborhood of the perturbation made of a finite number of periodicity cells. We construct Dirichlet to Neumenn conditions by combining the use of Partial Floquet Transforms, symmetry principles and the method previously developed for periodic waveguides.

6.3.5. Diffraction by infinite wires

Participants: Xavier Claeys, Patrick Joly, Houssem Haddar.

By adapting the variational method developed by Chandler-Wilde and Monk for rough surfaces, we have been able to develop the existence and uniqueness theory for the Helmholtz equation at the exterior of an infinitely long cylinder when the Dirichlet boundary condition is considered.

6.3.6. Integral equations

Participants: Edouard Demaldent, Marc Lenoir, Gary Cohen.

Since variational integral equation methods have been widely used for the solution of scattering problems, there has been much work devoted to the implementation of fast multipole methods, which address the computation of off-diagonal terms. Our recent work is a contribution to the computation of near-diagonal terms, whose difficulty seems to have been sometimes underestimated by engineers. Our formulas give the (almost) singular part of the integrals deriving from the solution of second order problems and must be completed by numerical integration techniques for the remainder. They must be considered as an alternative to purely numerical techniques. The method of calculation relies upon a quadrature formula for homogeneous functions which allows a recursive reduction of the dimension of the integration domain, provided there exists a convenient origin of the axes. A joint work with M. Duran of the Catholic University of Chile, devoted to the implementation of the method in the framework of integral equation methods is planned.

Édouard Demaldent (stage de DEA, Paris 6) studied the application of spectral elements to integral methods for the wave equation under the supervision of Gary Cohen. He started his PhD thesis at ONERA-Palaiseau in October on the same topic.

6.4. Absorbing boundary conditions and absorbing layers

6.4.1. Perfectly Matched Layers for time-harmonic aeroacoustics

Participants: Eliane Bécache, Anne-Sophie Bonnet-Ben Dhia, Guillaume Legendre.

We have developed a model using PMLs for the solution of the regularized Galbrun equation in an infinite waveguide. In the case of a uniform flow, we derived error estimates which are functions of the characteristic parameters of the layers (length and dumping coefficient). The results have been the object of a paper which has been accepted for publication in SINUM.

6.4.2. A hybrid DtN-PML method for elastic waveguides

Participants: Colin Chambeyron, Anne-Sophie Bonnet-Ben Dhia, Guillaume Legendre.

We consider the problem of time-harmonic diffraction in a 2D homogeneous and isotropic elastic waveguide. It is well-known that there exist, in some range of frequencies, inverse modes which have phase and group velocities of opposite signs. In presence of such inverse modes, PMLs do not work since they do not select the right outgoing solution. We developed a hybrid method which handles in an analytic way the inverse modes, PMLs being used for the remaining part of the solution. The method has been successfully applied to a simple scalar model. The extension to elastic waveguides is in progress.

6.4.3. Exact PML's with singularly growing absorption

Participants: Eliane Bécache, Andres Prieto.

We have worked on the extension to time dependent problems of exact PML's proposed by A. Bermúdez, L. Hervella and A. Prieto for the Helmholtz equation. The novelty is that the absorption term is authorized to go to infinity when one approaches the end of the layer (which permits to be exact for finite layers). The analysis is still not complete but first numerical results are quite encouraging.

6.4.4. Absorbing boundary conditions for time domain elastodynamics

Participants: Eliane Bécache, Mourad Ismaïl.

This is a work in progress. The objective is to give an alternative to PML's for the class of anisotropic media for which the PML technique does not work (see our previous works on instabilities of PML's).

6.4.5. Numerical schemes for Perfectly Matched Layers

Participants: Eliane Bécache, Andres Prieto.

We have investigated the question of the stability of numerical schemes for the discretizations of PML's for acoustic wave propagation. We have proposed a numerical scheme for PML's in corner regions which, contrary to some other schemes, does not affect the stability of the global scheme. This has been proven and validated experimentally.

6.5. Waveguides and resonances

6.5.1. Resonances of a plate in a moving confined flow

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

Adding to the real resonances, complex resonance frequencies have been proved to exist when both the fluid is in flow and the plate is elastic. We are still trying to find numerically such frequencies. We succeeded in the case of an incompressible fluid and the scenario of appearance of such resonance have been found: when the fluid is accelerated, a real frequency vanishes and becomes purely imaginary.

6.5.2. Periodic waveguides

Participants: Sonia Fliss, Patrick Joly, Jing Li.

We are concerned with the numerical simulation of locally perturbed periodic waveguides, such as Bragg Mirrors in electromagnetism.

We constructed and implemented (with mixed finite elements) exact boundary conditions for periodic waveguides with local perturbations using Dirichlet-to-Neumann operators.

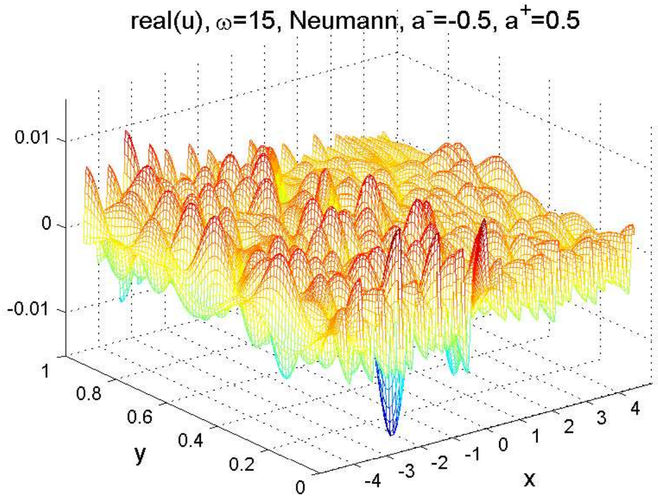


Figure 8.

6.5.3. Acoustic waveguides with absorbing walls

Participants: Anne-Sophie Bonnet-Ben Dhia, Jean-François Mercier, Sri Poernomo, Emmanuel Redon.

In collaboration with a researcher Emmanuel Redon and a PhD student Sri Poernomo from the University of Bourgogne, the propagation of sound in a waveguide with treated boundaries is investigated. First we focused on the determination of the duct modes. Contrary to the rigid wall case, treated boundaries lead to non self-adjoint problem. However we proved the completeness of the basis of the duct modes excepted for isolated values of the wall impedance. Then we developed a numerical method to solve scattering problems in such waveguides. It consists in coupling a finite element approximation to a modal expansion on the duct modes. Currently we investigate the influence of the presence of a uniform flow, which leads to new difficulties.

6.6. Asymptotic methods and approximate models

6.6.1. Asymptotic models for thin slots

Participants: Christophe Kirsch, Patrick Joly, David Sanchez, Sébastien Tordeux.

These works are in the continuation of the PhD thesis of S. Tordeux.

In the framework of the Post-Doc of D. Sanchez, we are deriving the construction and the analysis of a 2D-3D approximate model for the time harmonic (3D) Maxwell equations in media including thin slots.

In the framework of the Post-Doc of C. Kirsch, we are working on efficient numerical methods for treating such approximate models. A first solution consists in a mixed formulation of the transmission problem of the primal-dual type. the error analysis shows that this method does not suffer from any locking phenomenon.

In collaboration with S.Tordeux, we are investigating the construction of enriched Galerkin Methods exploiting the full asymptotic expansion of the solution for small slot aperture.

6.6.2. Generalized Impedance Boundary conditions for strongly absorbing obstacles

Participants: Marc Duruflé, Patrick Joly, Houssem Haddar, H.M. Nguyen.

We studied the derivation and theoretical justification of the generalized impedance boundary conditions in the case of harmonic electromagnetic scattering problem from imperfectly conducting obstacles with large conductivity. The 3-D electromagnetic problem is under study. We have provided some numerical experiments of validation in the latter case. We also proposed numerical solutions to treat the lack of optimal convergence rates for singular boundaries.

6.6.3. Wire approximation models

Participants: Xavier Claeys, Patrick Joly, Houssem Haddar.

In this new topic, we investigate the mathematical approach of approximate models for wave diffraction by thin wires through the method of matched asymptotics. We have applied the technique to a simplified 2D problem. The extension to the 3D case allowed us to recover well known models currently used by engineers : the Holland model and the Pocklington model.

6.6.4. Singularities for Maxwell equations

Participants: Patrick Ciarlet, Samir Kaddouri.

We model the corona discharge, around a 'rounded' corner. The goal is to determine the value of the charge density at the exact tip of this corner. To that aim, we compute the electrostatic potential in a domain, with a boundary that includes a 'rounded' corner of small curvature ϵ. The two dimensional case is now solved and in particular, an explicit relationship describing the value of the charge density (with respect to ϵ) has been established.

6.6.5. Approximate models for hydrodynamic instabilities

Participants: Patrick Joly, Anne-Sophie Bonnet-Ben Dhia, Kamel Berriri.

This new topic is developed within the framework of the PhD thesis of K. Berriri.
When one studies the propagation of sound in shear flows, one is faced to the apparition of well known instability phenomena : the Kelvin-Helholtz instability. This question is particularly crucial when the Mach profile of the flow presents strong variations: when one tries to model such flow with discontinuities, the natural transmission conditions lead to strongly ill-posed evolution problem. This clearly appears when one looks for the fundamental solution of Galbrun's equation via the Cagniard-De Hoop's method which, in addition to classical phenomena observed in presence of diopter (transmission-reflection phenomena, head waves), clearly exhibits the contribution the instability waves.
Using asymptotic analysis and boundary layer techniques, we have been able to propose approximate transmission conditions that lead to a well posed problem and permit us to model hydrodynamic instabilities.

The implementation of this new model in the framework of Galbrun's equations is under way.

6.7. Imaging and inverse problems

6.7.1. Near-field sampling methods

Participant: Houssem Haddar.

We developed new sampling methods to image embedded scatterers from Cauchy electromagnetic data at a given boundary. The formulation of the new method is based on the so-called reciprocity gap principle and has the advantage of avoiding the need for the background Green tensor, in comparison with the classical linear sampling method. The application of this method in the context of mines detection problem has been studied in the 2-D case [26]. We are currently working on the extension to the 3-D Maxwell's equations and anisotropic media.

6.7.2. The back-scattering convex support

Participant: Houssem Haddar.

We extended the inversion method introduced by Kusiak-Sylvester to the case where measurements are constituted by back-scattering amplitude instead of the farfield pattern. This method enables the reconstruction of an approximation of the convex-hull of a scatterer. We provide a complete justification for the linearized problem (using Born approximation). However, only partial results are proved for the non-linear case.

6.7.3. Inverse crack problem

Participants: Houssem Haddar, Fabrice Delbary.

The first results on explicit reconstructions formulas for the inverse (acoustical) planar crack problem are now generalized to the impedance problem. We also studied the stability of the inverse problem and proved local Lipschitz continuity for basic deformations of planar geometries (of the crack). We are currently investigating the extension of the sampling method to the reconstruction of crack from the Dirichlet to Neumann map at a given boundary.

6.7.4. Conformal mapping and the inverse electrostatic problem

Participant: Houssem Haddar.

We investigate the use of conformal mapping in the context of 2-D inverse boundary value problems for the Laplace equation. The algorithm based on this technique have been suggested by Akduman and Kress. The purpose of our work is to widen the applicability of the method in the Dirichlet case and to extend it to the Neumann case. The extension to impedant problem is under study.

6.7.5. Quasi-reversibility

Participant: Laurent Bourgeois.

A very recent contribution concerns the quasi-reversibility method to solve ill-posed Cauchy problems for an elliptic equation. It consists of transforming the initial second-order and ill-posed problem into a family (depending on a small parameter) of fourth-order and well-posed problems. This method, which was first proposed 40 years ago, still arises questions, from a theoretical and a numerical point of view. We developed a mixed formulation of quasi-reversibility which enables the use of simple finite elements, while cumbersome finite elements were required with the classical formulation. Besides, there is some work in progress concerning the convergence rate of the method and the optimal choice of the regularization parameter.

6.7.6. Time reversal

Participants: Christophe Hazard, C. Ben Amar.

A numerical simulation of D.O.R.T. method for intrusive time-reversal mirrors has been implemented in the context of our code MELINA. It shows in particular how the focusing properties depend on the different parameters of the problem (frequency, interactions between the different obstacles, and with the mirror...). The transient aspect of time-reversal is now investigated: in particular, the link between the time-harmonic and time-dependent time reversal operators has been established.

6.8. Recents developpements of software MELINA

Participants: Eric Lunéville, Colin Chambeyron, Daniel Martin.

The new version of Melina, written in C++ has been presented to the melina users during a special meeting (Le Croisic, may 15-19 2005). This is a primary version which includes only some basic tools : mesh tools, elementary finite element computation and a direct solver. All the main structures (C++ classes) have been well defined and they are currently being implemented.

7. Contracts and Grants with Industry

7.1. Contract ENSTA-DGA

Participants: Patrick Ciarlet, Christophe Hazard, Erell Jamelot, François Loret.

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 INRIA-EDF

Participants: Julien Diaz, Patrick Joly.

The object of this collaboration is the modelization of the structural noise for crack detection in welds by ultrasonic waves.

7.3. Contract INRIA-EADS-1

Participants: Gary Cohen, Pascal Grob, Patrick Joly.

This contract is about the numerical simulation of time dependent vibro-acoustics phenomena using coupled methods (3D / 2D finite elements, retarded potentials / 2D finite elements)

7.4. Contract INRIA-EADS-2

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.

7.5. Contract ENSTA-EADS

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.

7.6. Contract INRIA-Airbus

Participants: Abdelaâziz Ezziani, Patrick Joly.

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

7.7. Contract INRIA-ONERA Palaiseau

Participants: Gary Cohen, Marc Duruflé.

This contract is about the numerical simulation of time harmonic wave propagation using higher order discretization methods (mixed finite elements, Discontinuous Galerkin)

7.8. Contract INRIA-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

- A project of the ANR in collaboration with IEF (Institut d'Electronique Fondamentale) of the University of Orsay has been accepted. It concerns the modelization of micro and nano-structures in optics.
- We participate (administratively and scientifically) to the GDR Ultrasons which regroups 12 research laboratories in Acoustics and Applied Mathematics) working on nondestructive testing.
- We have been involved in several scientific manifestations of the GDR Ondes.

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.

9. Dissemination

9.1. Various academic responsibilities

- E. Bécache was member of the evaluation committee of INRIA.
- A. S. Bonnet-Ben Dhia is a member of the Conseil Scientifique de Département of SPI at CNRS.
- H. Haddar is editor of the special issue of the Journal Computational and Applied Mathematics that follows the Waves2005 Conference.
- H. Haddar has been involved in the organization of the Conference TAMTAM (Tunis, April 2005)
- P. Joly was a member of the Editorial Board of M2AN (Mathematical Modeling and Numerical Analysis).
- P. Joly is a member of the Book Series Scientific Computing of Springer Verlag.
- P. Joly was a member of the Editorial Board of M2AN (Mathematical Modeling and Numerical Analysis).
- P. Joly is a member of the Commission de Spécialistes of the University Paris VII.
- P. Joly is a member of the Post Docs Commission of INRIA Rocquencourt.
- P. Joly was co-organizer (with V. Gobin of ONERA) of the Journée Scientifique ONERA on Mathematical and Numerical Modeling in Electromagnetism. He is editor of the corresponding special issue of the Comptes Rendus de l'Académie des sciences.
- M. Lenoir is a member of the Commission de Spécialistes of CNAM.
- J. Li has organized a minisymposium on Mathematical Modeling in Optics at the Conference Enumath2005, Santiago de Compostela, Spain, July 2005.
- The Project organizes the monthly Seminar Poems.
- The Project has been actively involved in the Waves2005 Conference in Brown University (June 2005, Providence, USA) (Scientific and organization committees).
- The Project has been actively involved in the organization of the Journées Melina (le Croisic - May 2005)
- Organization of “Théorie spectrale pour l'acoustique”, ENSTA, Paris, 2005
- Inauguration of the UMR Poems at ENSTA Rocquencourt, December 2005. Presentation by A. S. Bonnet-Ben Dhia and P. Joly.

9.2. Teaching

All members of Project POEMS, permanent or not, are very much involved in teaching. The location of a part of the team in the Ecole Nationale des Techniques Avancées (ENSTA) has naturally let us to invest particularly this school, but we also teach in several other institutions in the Paris area : Ecole Polytechnique, Ecole Centrale de Paris, Ecole des Mines de Paris, Ecole Supérieure d'Ingénieurs Léonard de Vinci, ENS of Cachan, Université Paris IX (Dauphine) and Paris VI (Jussieu), UVSQ (Université de Versailles-Saint Quentin). Finally, we are also sollicited for teaching in other places in France (Université de Bordeaux I) and in foreign countries (Ecole Nationale des Ingénieurs de Tunis in Tunisia, Université de Santiago de Compostela in Spain).
We detail below for each permanent member the institutions where he/she has given lectures (recitations are omitted) during the last four years: (en excluant l'encadrement de travaux dirigés ou pratiques).

- *Eliane Bécache*
  ENSTA (graduate course)
  ENIT (Master of applied mathematics)
- *Anne-Sophie Bonnet-Ben Dhia*
  ENSTA (undergraduate and graduate courses)
  ENIT (Master of applied mathematics)
  Université Paris VI (DEA of Mechanics)
  Ecole Centrale de Paris (DEA of Mechanics)
- *Patrick Ciarlet*
  ENSTA (undergraduate and graduate courses)
  Université de Versailles-Saint Quentin (DEA of Mathematics and Physics)
- *Gary Cohen*
  Université Paris IX (DEA of Applied Mathematics)
- *Christophe Hazard*
  ENSTA (graduate course)
  ENIT (Master of applied mathematics)
  Université Paris VI (DEA of Mechanics and DEA of Numerical Analysis)
- *Houssem Haddar*
  ENSTA (graduate courses)
  Ecole des Mines de Paris (graduate courses)
- *Patrick Joly*
  ENSTA (graduate courses)
- *Marc Lenoir*
  ENSTA (graduate course)
  ENS Cachan (Preparation to agrégation)
- *Jing Li*
  ENSTA (graduate course)
- *Eric Lunéville*
  ENSTA (graduate and postgraduate courses)
- *Jean-François Mercier*
  ENSTA (postgraduate course)

9.3. Participation in Conferences, Workshops and Seminars

- E. Bécache
  - *Analysis of Numerical Methods for Coupling Heterogeneous Media or Models*, ECCOMAS Thematic Conference on Coupled Problems, Santorini, Greece, May 25-28,
  - Invitation at the LAMSIN of ENIT, Tunis (8-17 April)
  - Invitation at the department of Applied Mathematics of the University of Santiago de Compostela (12-19 July)
  - *Perfectly matched layers for time-harmonic acoustics in the presence of a uniform flow*, Enumath2005, Santiago de Compostela (Spain), July 2005.
- C. Ben Amar
  - *Retournement temporel dans un guide d'ondes, étude theéorique et numérique*, Premier Congrès International de Conception et Modélisation des Systèmes Mécaniques, Hammamet, Tunisie, March 2005.
  - *Modélisation mathématique d'un miroir à retournement temporel*, Conference TAMTAM'05 , Tunis, Avril 2005.
  - *Mathematical and numerical study of a time reversal mirror*, Waves 2005, Brown University, Providence, USA, June 2005.
- K. Berriri
  - *Régularisation de l'équation de Galbrun pour l'aéroacoustique en régime transitoire*, Conference TAMTAM'05, Tunis, April 2005
  - *Numerical analysis of time-dependent Galbrun equation in an infinite duct.* Waves2005, Brown University, Providence(USA), June 2005.
  - *Modèle approche pour la simulation de l'instabilité de Kelvin-Helmhotz dans un écoulement discontinu.* Jounées d'Etudes sur la propagation acoustique en écoulement, Angers, October 2005.
- A.S. Bonnet-Ben Dhia
  - *PML pour l'aéroacoustique en régime périodique établi*, Laboratoire de Mathématiques Appliquées, Pau, February 2005.
  - *PML pour l'aéroacoustique en régime périodique établi*, Laboratoire de Mécanique et Acoustique, CNRS, Marseille, February 2005. 2005
  - *Couches Absorbantes Parfaitement Adaptées pour la Simulation Numérique des Ondes de Lamb*, Journées d'Acoustique Physique Sous-marine et Ultra-Sonore, Aix-en-Provence, April 2005 (invited lecture).
  - *Une méthode hybride PML/EFL pour la diffraction dans un guide d'ondes*, Journées Melina, Le Croisic, May 2005.
  - Participation à Waves2005, Brown University, Providence(USA), June 2005.
- L. Bourgeois

  - *Localisation d'un obstacle dans un océan 3D de profondeur finie* Journées Melina, Le Croisic, May 2005.
  - *Locating an obstacle in a 3D finite depth ocean using the convex scattering support,* Waves2005, Brown University, Providence(USA), June 2005.
  - *Une formulation mixte de la quasi-réversibilité pour résoudre le problème de Cauchy des EDP elliptiques,* JANO8, Rabat, Morocco, December 2005

- N. Castel

  - *Discontinuous Galerkin Q_r. Applications in aeroacoustics,* Waves2005, Brown University, Providence(USA), June 2005.
  - *Discontinuous Galerkin Q_r. Applications in aeroacoustics,* CEMRACS, CIRM, Marseille, July 2005.
  - *Une méthode de Galerkin discontinue appliquée à l'équation de Galbrun.* Jounées d'Etudes sur la propagation acoustique en écoulement, Angers, October 2005.

- C. Chambeyrom

  - *Nouveaux Solveurs pour Melina++* Journées Melina, Le Croisic, May 2005.

- G. Cohen

  - Participation aux journées Melina, Le Croisic, May 2005.

- F. Delbary

  - *Reconstruction de l'impédance d'une fissure à partir de mesures acoustiques* Conference TAMTAM'05, Tunis, April 2005
  - *Reconstruction of the impedance of a crack from acoustical measurements* Waves2005, Brown University, Providence(USA), June 2005.

- E. M. Duclairoir

  - *Numerical simulation of acoustic propagation in a shear flow in the frequency domain.* Waves2005, Brown University, Providence(USA), June 2005.
  - *Simulation numérique du rayonnement d'ondes acoustiques dans un écoulement cisaillé en régime périodique établi.* Journées d'Etudes sur la propagation acoustique en écoulement, Angers, October 2005.

- M. Duruflé

  - *Elements finis d'ordre élevé pour l'équation de Helmholtz,* Journées Melina. Le Croisic, May 2005.
  - *Comparison of Higher-Order Finite Element Methods for the 2-D Maxwell's Equations in Frequency Domain,* Waves2005, Brown University, Providence(USA), June 2005.
  - *Asymptotic models for Electromagnetic Scattering from Strongly Absorbing Obstacles,* Waves2005, Brown University, Providence(USA), June 2005.

- A. Ezziani
  - *A mixed finite element method and an explicit scheme for wave propagation in viscoelastic time domain*, Jano8, Rabat, Morocco, December 2005 .
  - *Ondes dans les milieux poroélastiques, éléments finis d'ordre élevés,* TAMTAM'05, Tunis, Tunisia, Mai 2005.
  - *Modélisation mathématique et numérique de la propagation d' ondes dans les milieux viscoélastiques et poroélastiques*, Séminaire de l'IFP, Rueil-Malmaison, France, Mars 2005.
- S. Fliss
  - *Opératuers DtN dans les guides d'onde périodiques et complétude des modes de Floquet*, "Théorie spectrale pour l'acoustique", ENSTA, Paris, Juin 2005.
- P. Grob
  - *Régularisation de l'équation de Galbrun pour l'aéroacoustique en régime transitoire,* Conference TAMTAM, Tunis, April 2005
  - *Elements finis mixtes spectraux d'ordres élevés pour la vibroacoustique instationnaire*, Journées Melina. Le Croisic, May 2005.
  - *Coupling finite elements and integral equations in time domain vibroacoustics,* Waves2005, Brown University, Providence(USA), June 2005.
  - *Mixed Higher Order Spectral Elements for Vibroacoustics in Time Domain,* Waves2005, Brown University, Providence(USA), June 2005.
  - *Quelques méthodes numériques pour la vibroacoustique instationnaire,* Séminaire du GIREF, Québec, Canada, July 2005.
- H. Haddar
  - *Generalized impedance boundary conditions for strongly absorbing scatterers: various approximations and error analysis*, Seminar at the University of Göttingen, Germany, February 2005 (Invitation for one week). for Strongly Absorbing Scatterers
  - *Electrostatic Imaging Based on Conformal Mapping.* Conférence GAMM'05, Luxembourg, April 2005.
  - *Imaging buried objects from electromagnetic measurements,* Waves05, Brown University , Providence, USA, June 2005.
  - *Generalized impedance boundary conditions for strongly absorbing scatterers: various approximations and error analysis,* Seminar at the University of Delaware, USA, June 2005(Invitation for one week).
  - *Asymptotic Models in Electromagnetism : Example of Generalized Impedance Boundary Conditions For Strongly Absorbing Media*, JSO "Modelisation EM", ONERA, Toulouse, Mars 2005.
- C. Hazard
  - Participation aux journées Melina, Le Croisic, May 2005.

  - *Développement en modes résonnants pour le problème transitoire,* "Théorie spectrale pour l'acoustique", ENSTA, Paris, Juin 2005.
  - Participation à Waves2005, Brown University, Providence(USA), June 2005.

- E. Jamelot

  - Oral presentation at the 4ème séminaire des Journées Singulières, Nancy.
  - Poster presentation at the 36ème Congrès d'Analyse Numérique, Strasbourg, Mai 2005.
  - *Nodal finite element methods for solving Maxwell equations.* Enumath2005, Santiago de Compostela (Spain), July 2005.

- P. Joly

  - *Conditions d'impédance généralisées pour la diffraction d'ondes par des obstacles fortement conducteurs*. Seminar at the Ecole Nornale Supérieure de Cachan - Antenne de Bretagne, Rennes, Mars 2005.
  - Participation aux journées Melina, Le Croisic, May 2005.
  - *Mathematical analysis of time domain PML's* Waves2005, Brown University, Providence(USA), June 2005.
  - *Coupling retarded potentials and finite elements for time domain vibroacoustics* Enumath2005, Santiago de Compostela (Spain), July 2005.
  - *Exact boundary conditions for locally perturbed periodic waveguides,* Enumath2005, Santiago de Compostela (Spain), July 2005.
  - *Numerical methods for elastic wave propagation,* 2 conferences at the Summer School of GDR ONDES, Sup Elec, Gif-sur-Yvette, September 2005.
  - *Exact boundary conditions for locally perturbed periodic waveguides,* Waves Meeting, University of Reading (England), September 2005 (invited lecture).
  - *Propagation of Electromagnetic Waves in a Locally Perturbed Periodic Waveguide,* Workshop TiSCoPDE05, September 2005, Berlin, Germany (invited lecture)
  - *Modèles approchés pour la modélisation de la propagation du son dans des écoulements discontinus,* Journées Scientifiques du GDR Ondes, Besançon, November 2005 (invited lecture)
  - *Propagation of Waves in a Locally Perturbed Periodic Media,* Workshop WIP2005, December 2005, CIRM, Marseille (invited lecture)
  - *Un modèle approché stable pour l'aéroacoustique en écoulement discontinu,* Séminaire Poems, ENSTA, Paris, December 2005

- C. Kirsch

  - *Non-reflecting boundary conditions for wave scattering problems in unbounded domains.* Séminaire Poems, ENSTA, Paris, Movember 2005

- M. Lenoir

  - Participation aux journées Melina, Le Croisic, May 2005.
  - Invitation at the Universidad Catolica del Chile (M.Duran), December 2005.

- F. Loret
  - *Décomposition en modes résonnants pour le problème de tenue à la mer, application numérique*, 10èmes Journées de l'Hydrodynamique, Poitiers, Mars 2005.
  - *The Singularity Expansion Method applied to a transient fluid-structure interaction problem* Waves2005, Brown University, Providence(USA), June 2005.
- E. Lunéville
  - Participation aux journées Melina, Le Croisic, May 2005.
  - *Generalized impedance boundary conditions in acoustics with flow*, Waves2005, Brown University, Providence(USA), June 2005.
- J. F. Mercier
  - Participation aux journées Melina, Le Croisic, May 2005.
  - *Influence of the coupling of an elastic plate with a confined flow on resonances.* Waves2005, Brown University, Providence(USA), June 2005.
- C. M. Zwölf
  - *Une approche variationnelle d'un problème de transmission électromagnétique entre deux milieux à constantes diélectriques de signes opposés*, Le Croisic, May 2005.
  - *A variational approach for wave transmission between media with opposite sign dielectric constants*, Waves2005, Brown University, Providence(USA), June 2005.
  - Poster presentation at the Journées Scientifiques du GDR Ondes, Besançon, November 2005

10. Bibliography

Doctoral dissertations and Habilitation theses

[1] J. DIAZ. *Approches analytiques et numériques de problèmes de transmission en propagation d'ondes en régime transitoire. Application au couplage fluide-structure et aux méthodes de couches parfaitement adaptées*, Ph. D. Thesis, Université Paris 6, 2005.

[2] A. EZZIANI. *Modélisation mathématique et numérique de la propagation d'ondes dans les milieux viscoélastiques et poroélastiques*, Ph. D. Thesis, Université Paris 9, 2005.

[3] E. JAMELOT. *Résolution des équations de Maxwell avec des éléments finis de Galerkin continus*, Ph. D. Thesis, Ecole Polytechnique, november 2005.

Articles in refereed journals and book chapters

[4] F. ASSOUS, P. CIARLET, E. GARCIA. *Singular electromagnetic fields: inductive approach*, in "C. R. Math. Acad. Sci. Paris", vol. 341, n^o 10, 2005, p. 605–610.

[5] A. BEN ABDA, F. DELBARY, H. HADDAR. *On the use of the reciprocity-gap functional in inverse scattering from planar cracks*, in "Math. Models Methods Appl. Sci.", vol. 15, n^o 10, 2005, p. 1553–1574.

[6] K. BERRIRI, A.-S. BONNET-BEN DHIA, P. JOLY. *Régularisation de l'équation de Galbrun pour l'aéroacoustique en régime transitoire*, in "ARIMA", to appear.

[7] A.-S. BONNET-BEN DHIA, 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", to appear.

[8] A. S. BONNET-BEN DHIA, D. DRISSI, N. GMATI. *Mathematical analysis of the acoustic diffraction by a muffler containing perforated ducts*, in "Math. Models Methods Appl. Sci.", vol. 15, n^o 7, 2005, p. 1059–1090.

[9] A.-S. BONNET-BEN DHIA, E.-M. DUCLAIROIR, G. LEGENDRE, J.-F. MERCIER. *Time-harmonic acoustic propagation in the presence of a shear flow.*, in "Journal of Computational and Applied Mathematics", to appear.

[10] L. BOURGEOIS. *A mixed formulation of quasi-reversibility to solve the Cauchy problem for Laplace's equation*, in "Inverse Problems", vol. 21, 2005, p. 1087-1104.

[11] E. BÉCACHE, A.-S. BONNET-BEN DHIA, G. LEGENDRE. *Perfectly matched layers for time-harmonic acoustics in the presence of a uniform flow*, in "SIAM Journal on Numerical Analysis", to appear.

[12] E. BÉCACHE, A. CHAIGNE, G. DERVEAUX, P. JOLY. *Numerical simulation of a guitar*, in "Comput. & Structures", vol. 83, n^o 2-3, 2005, p. 107–126.

[13] E. BÉCACHE, G. DERVEAUX, P. JOLY. *An efficient numerical method for the resolution of the Kirchhoff-Love dynamic plate equation*, in "Numer. Methods Partial Differential Equations", vol. 21, n° 2, 2005, p. 323–348.

[14] E. BÉCACHE, A. EZZIANI, P. JOLY. *A mixed finite element approach for viscoelastic wave propagation*, in "Comput. Geosci.", vol. 8, n° 3, 2004, p. 255–299.

[15] E. BÉCACHE, P. JOLY, J. RODRÍGUEZ. *Space-time mesh refinement for elastodynamics. Numerical results*, in "Comput. Methods Appl. Mech. Engrg.", vol. 194, n° 2-5, 2005, p. 355–366.

[16] P. G. CIARLET, P. CIARLET. *Another approach to linearized elasticity and a new proof of Korn's inequality*, in "Math. Models Methods Appl. Sci.", vol. 15, n° 2, 2005, p. 259–271.

[17] P. CIARLET, B. JUNG, S. KADDOURI, S. LABRUNIE, J. ZOU. *The Fourier Singular Complement Method for the Poisson problem. Part I: prismatic domains*, in "Numer. Math.", to appear.

[18] P. CIARLET, B. JUNG, S. KADDOURI, S. LABRUNIE, J. ZOU. *The Fourier Singular Complement Method for the Poisson problem. Part II: axisymmetric domains.*, in "Numer. Math.", to appear.

[19] P. CIARLET. *Augmented formulations for solving Maxwell equations*, in "Comput. Methods Appl. Mech. Engrg.", vol. 194, n° 2-5, 2005, p. 559–586.

[20] M. CLAUSEL, M. DURUFLÉ, P. JOLY, S. TORDEUX. *A Mathematical Analysis of the Resonance of the Finite Thin Slots*, in "Applied Numerical Matehmatics", to appear.

[21] G. COHEN, S. FAUQUEUX. *Mixed spectral finite elements for the linear elasticity system in unbounded domains*, in "SIAM J. Sci. Comput.", vol. 26, n° 3, 2005, p. 864–884 (electronic).

[22] G. COHEN, X. FERRIERES, S. PERNET. *A Spatial High-Order Hexahedral Discontinuous Galerkin Method to Solve Maxell's Equations in Time Domain*, in "J. of Computational Physics", to appear.

[23] G. COHEN, X. FERRIERES, S. PERNET. *High Spatial Order Finite Element Method to Solve Maxwell's Equations in Time Domain*, in "IEEE Trans on Antennas and Propagation", vol. 53, n° 9, 2005.

[24] G. COHEN, P. GROB. *Mixed Higher Order Spectral Finite Elements for Reissner Mindlin Equations*, in "SIAM journal SISC", to appear.

[25] F. COLLINO, T. FOUQUET, P. JOLY. *Conservative space-time mesh refinement methods for the FDTD solution of Maxwell's equations*, in "J. Comput. Phys.", vol. 211, n° 1, 2006, p. 9–35.

[26] D. COLTON, H. HADDAR. *An application of the reciprocity gap functional to inverse scattering theory*, in "Inverse Problems", vol. 21, n° 1, 2005, p. 383–398.

[27] J. DIAZ, P. JOLY. *A time domain analysis of PML models in acoustics*, in "CMAME", to appear.

[28] J. DIAZ, P. JOLY. *An analysis of higher order boundary conditions for the wave equation*, in "SIAM J. Appl. Math.", vol. 65, n° 5, 2005, p. 1547–1575 (electronic).

[29] J. DIAZ, P. JOLY. *Robust high order non-conforming finite element formulation for time domain fluid-structure interaction*, in "J. Comput. Acoust.", vol. 13, n^o 3, 2005, p. 403–431.

[30] M. DURUFLÉ, H. HADDAR, P. JOLY. *High order generalized impedance boundary conditions in electromagnetic scattering problems.*, in "C. R. Acad. Sci. Paris Sér. I Math.", to appear.

[31] H. HADDAR, P. JOLY, H.-M. NGUYEN. *Generalized impedance boundary conditions for scattering by strongly absorbing obstacles: the scalar case*, in "Math. Models Methods Appl. Sci.", vol. 15, n^o 8, 2005, p. 1273–1300.

[32] H. HADDAR, R. KRESS. *Conformal mappings and inverse boundary value problems*, in "Inverse Problems", vol. 21, n^o 3, 2005, p. 935–953.

[33] H. HADDAR, S. KUSIAK, J. SYLVESTER. *The Convex Back-Scattering Support.*, in "SIAM J. Appl. Math.", vol. 66, n^o 2, 2005, p. 591–615 (electronic).

[34] E. JAMELOT. *Corrigendum to the note: "Nodal finite element methods for Maxwell's equations" [C. R. Math. Acad. Sci. Paris **339** (2004), no. 11, 809–814; MR2110386]*, in "C. R. Math. Acad. Sci. Paris", vol. 340, n^o 5, 2005, p. 409–410.

[35] S. JOB, E. LUNÉVILLE, J.-F. MERCIER. *Diffraction of an acoustic wave by a plate in a uniform flow: a numerical approach*, in "J. of Comp. Acoustics", to appear.

[36] P. JOLY, J. RODRÍGUEZ. *An error analysis of conservative space-time mesh refinement methods for the one-dimensional wave equation*, in "SIAM J. Numer. Anal.", vol. 43, n^o 2, 2005, p. 825–859 (electronic).

[37] P. JOLY, S. TORDEUX. *Matching of asymptotic expansions for wave propagation in media with thin slots (I) The asymptotic expansion*, in "Multiscale Modeling and Simulation: A SIAM Interdisciplinary Journal", to appear.

[38] J. LI. *Low order approximation of the spherical nonreflecting boundary kernel for the wave equation.*, in "Linear Algebra and its Applications", to appear.

[39] S. TORDEUX, P. JOLY. *An asymptotic analysis of time harmonic waves in media with thin slots*, in "ESAIM: Mathematical Modelling and Numerical Analysis", to appear.

Internal Reports

[40] P. JOLY, M. LENOIR, S. TORDEUX. *Modèles asymptotiques pour la propagation des ondes dans des milieux comportant des fentes*, Technical report, n^o RR-5568, INRIA, 2005, http://www.inria.fr/rrrt/rr-5568.html.

[41] P. JOLY, S. TORDEUX. *Matching of asymptotic expansions for wave propagation in media with thin slots. (I) The asymptotic expansion*, Technical report, n^o 2005-08, ETHZ, Seminar for applied mathematics, 2005.

[42] S. TORDEUX. *Un problème de Laplace non standard en milieu non borné*, Technical report, n^o RR-5799, INRIA, January 2006, http://www.inria.fr/rrrt/rr-5799.html.