INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Ondes

Modeling and Simulation of Wave Propagation Phenomena

Rocquencourt

THEME NUM

Activity Report

2004

Table of contents

1. Team

Heads of project team
Patrick Joly [DR]
Anne-Sophie Bonnet-Ben Dhia [DR-CNRS]

Vice-head of project team
Eliane Bécache [CR]

Administratives assistants of project team
Sylvaine Sperte [CDD until 30/11/2004]
Helena Kutniak [CDD for 01/12/2004]
Annie Marchal [Secretary at ENSTA]

Permanent INRIA researchers
Gary Cohen [CR]
Houssem Haddar [CR]
Jing-Rebecca Li [CR]

Permanent CNRS researchers
Marc Lenoir [DR]
Christophe Hazard [CR]
Jean-François Mercier [CR]

Permanent ENSTA researchers
Laurent Bourgeois [Assistant professor]
Patrick Ciarlet [Professor]
Eric Lunéville [Assistant professor]

Exterior collaborators
Denis Matignon [Assistant professor, ENS Telecom]
Daniel Martin [Assistant professor, University of Rennes]
Christine Poirier [Assistant professor, University of Versailles-Saint Quentin]

Engineers
Colin Chambeyron [CNRS]

Visiting researchers
Amel Ben Abda [ENIT Tunis]
David Colton [University of Delaware]
Fioralba Cakoni [University of Delaware]
Nabil Gmati [ENIT Tunis]
Tom Hagström [University of New Mexico]
Jan Hesthaven [Brown University]
Rainer Kress [University of Göttingen]
Peter Petropoulos [New Jersey University]

Chercheurs Post-Doctorants
Steven Kusiak [post doct CNRS]
Mourad Ismaïl [post doct INRIA]

PhD Students
Choukri Ben Ammar [Ecole Polytechnique Tunis, (advisor C. Hazard)]
Kamel Berriri [boursier tunisien, Univ. Paris 9, (advisors A.S. Bonnet-Ben Dhia and P. Joly)]
Nicolas Castel [boursier MENRT, University Paris 9, (advisor G. Cohen)]
Isabelle Champagne [Personnel DGA, Ecole Polytechnique, (advisor J. Henry)]
Fabrice Delbary [boursier MENRT, University Paris 6, (advisor H. Haddar)]

Julien Diaz [boursier MENRT, University Paris 6, (advisor P. Joly)]
Eve-Marie Duclairoir [bourse BDI CNRS/EADS, (advisors A.S. Bonnet-Ben Dhia, J. F. Mercier)]
Marc Duruflé [boursier Inria, University Paris 9, (advisor G. Cohen)]
Abdelaâziz Ezziani [boursier MENRT, University Paris 9, (advisor sE. Bécache, P.Joly)]
Pascal Grob [boursier CIFRE EADS, G. Cohen, (advisor P. Joly)]
Erell Jamelot [boursier DGA, Ecole Polytechnique, (advisor P. Ciarlet)]
Samir Kaddouri [boursier MENRT, Orsay, P. Ciarlet]
François Loret [boursier MENRT, Ecole Centrale de Paris, (advisor C. Hazard)]
Sébastien Pernet [boursier ONERA, (advisor G. Cohen)]
Jerónimo Rodríguez García [boursier Inria, University Paris 9, (advisors E. Bécache, P. Joly)]
Gilles Scarella [boursier Inria, University Paris IX]
Sébastien Tordeux [boursier DGA, University Versailles-St Quentin, (advisor P. Joly)]
Carlo-Maria Zwölf [Versailles-St Quentin, (advisors A.S. Bonnet-Ben Dhia and P. Ciarlet)]

2. Overall Objectives

The common project between INRIA, CNRS and ENSTA will evolve in the next few weeks. The project is becoming an UMR (Unité Mixte de Recherche) of CNRS. The signing of the convention between INRIA, CNRS and ENSTA is expected to take place before the end of the year and the creation of the new entity should be official, in case of a positive evaluation, in January 2005. The name of the Project will change at the same time. The new name will be POEMS for “Propagation d’Ondes : Étude Mathématique et Simulation”.

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), 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 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

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 Ondes.

4. 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 10th 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

Warning. *This paragraph summarizes the research activity of the Project during the period 2001-2004. Since they have left the project, we have chosen not to mention the works on J. D. Benamou on high frequency optics and J. Henry on the factorization of elliptic operators (a topic which is over present in our text through the thesis of I. Champagne). Their publications (written during their period at ONDES) are however included in the reference list at the end of this document.*
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

Wave propagation problems are by nature evolution problems and it is important to have efficient (or well-performing) numerical methods to solve such problems directly in the time domain. An important part of the research activity of the Project is devoted to the development and analysis of such methods.
For numerical methods, one can proceed in (at least) two ways to achieve “good performance”.

- One consists of emphasizing the accuracy of the result without sacrificing too much the speed of the calculation. In this spirit are our works on spectral finite elements [2] or those, more recently, on higher order discontinuous Galerkin methods. The main characteristics of the methods we developped are based on the use of quadrilateral (hexahedral) meshes, appropriate vector field transforms (from the reference element to the current element) and quadrature formulae. Initially designed for acoustic waves, these methods have been successfully extended to elastic waves (thesis of S. Fauqueux in collaboration with IFP, see [63], [64]) and electromagnetic waves (thesis of S. Pernet in collaboration with ONERA). Our current work concerns the extension to linearized Euler equations for applications to aeroacoustics (thesis of N. Castel). The work of J. Li (in collaboration with L. Greengard [30]) on the discretization of an exact three time step integral formula for the scalar wave equation also falls into this category.
- The other approach aims foremost at achieving the rapidity and the robustness of the calculation, without sacrificing too much its accuracy. With this objective, we have been developing for several years the fictitious domain method for diffraction problems. Such a method is certainly not efficient in all cases but we have found certain applications for which we got spectacular results, such as the diffraction of elastic waves by cracks (see [52]) or the numerical modelling of the guitar (see [70]). Finally we have made some progress in the analysis of the method in elastodynamics, a case that poses new difficulties (see [53]).

However it appears more and more clearly that there is no universal method which allows us to solve any kind of problem with the best efficiency. That is why much work in the waves community is concerned with the construction of hybrid methods aiming at coupling different approaches. In this direction, our more recent works have been developing along three lines (these methods belong to a general class of conservative variational methods, a general presentation of which is the subject of the review paper [81]):

- Conservative space-time mesh refinement methods. This work was initiated in for Maxwell's equations with the thesis of T. Fouquet (contract with CEG). There was no satisfactory solution to this question in the literature before (in our opinion). The variational method that we have developed is, to our knowledge, the first non-conforming mesh refinement algorithm for explicit schemes whose stability is guaranteed from the theoretical point of view (see [66], [21]). It is based on a decomposition approach using Lagrange multipliers to handle in a weak way some artificial transmission conditions and a clever time stepping procedure that ensures the conservation of some discrete energy. More recently, this method has been extended [35] and improved [18] for elastodynamics equations in the PhD thesis of J. Rodriguez, who has also considered the coupling of this method with the fictitious domain method. This has been applied to the numerical modelling of non-destructive testing experiments (research contract with EDF). One of the exciting aspects of this work is the analysis of the method that is better and better understood and which involves non standard phenomena and techniques (see [65], [29]).
- Coupling methods for time dependent fluid-structure interaction problems. Our objective was to simulate wave propagation in fluid-solid media, which occurs, for example, at the bottom sea in underwater seimics (contract with IFREMER) or when one is modeling the propagation of ultrasounds in bones (collaboration with the laboratory LIP of Paris 6). More precisely, we want to be able to couple, in a stable way, two different numerical methods in the solid and fluid domains respectively, allowing the use of non conforming grids and different time steps. This is achieved with a variant of the variational method mentioned above which has the advantage of being multiplier free (see [81], [23]).
- Coupling boundary elements (retarded potentials) and volume finite elements in vibro-acoustics. This research is along continued in collaboration with EADS (for applications to ...) with the PhD thesis of P. Grob. Here the new difficulty lies in the different nature of the methods used for the fluid part (based on integral representations, non-local in time) and the thin structure (based on finite element in space and finite differences in time). We have designed a coupling algorithm which seems to be the first for which a stability result can be established.

Finally, we are interested in formulating methods which are specifically designed to improve the calculation of a part of the solution. This is for example the case of:

- The Singularity Expansion Method which aims at exploiting a particular expansion of the solution of a problem into the so-called resonant modes (it generalizes the eigenmode decomposition - see the habilitation of C. Hazard [80]) to better take into account the behaviour of the solution of the transient problem for large times. This technique has been developed more specifically for the application to the sea-keeping problem with the thesis of F. Loret (see [39]) .
- The Singular Complement Method for treating diffraction problems in singular domains in order to improve the treatment of the solution at the neighborhood of geometrical singularities of the computational domain. This question is of particular interest for Maxwell's equations and raises subtle questions of functional analysis that are now rather well understood ([40], [61]). The method had been previously designed and tested in 2D. Its extension to general 3D problems appears to be quite difficult and the more recent developments concern Maxwell equations in axisymmetric domains (subject of the PhD theses of E. Garcia [74], S. Kaddouri and E. Jamelot) for which one can reduce the original 3D problem to a series of 2D problems that can not be transformed into scalar problems (contrary to the pure 2D Maxwell's system).

6.3. Numerical modelling of complex problems

The recent progress in terms of numerical methods allows us to take into full account more and more complex and realistic phenomena. During the past years, in collaboration with physicists or engineers (these contacts are particularly important in the discussion and the construction of an appropriate model), we have been working on:

- The numerical modelling of visco-elastic wave propagation. This work has been initiated within a collaboration with IFREMER and pursued through contacts with SHELL. Our objective, which we have reached successfully (see [49], [17]) was to extend the original mixed finite element methods developed for the purely elastic case to a general class of linear visco-elastic materials (generalized Zener's models).
- The modeling of waves in poro-elastic media. This work, which constitutes the second part of the thesis of A. Ezziani, is developed in the framework of a research contract with SHELL. Our objective is to adapt the use of hexaedral spectral elements initially designed by S. Fauqueux for elastic waves to general porous media (generalized Biot models).
- The modeling of acoustic waves in flows using the so-called Galbrun's model. This model is an alternative to linearized Euler equations which seems to be well suited to the use of finite element methods provided that adapted regularisation techniques are applied (see also the work about on Galbrun's equations in the time harmonic regime). This is the subject of the PhD thesis of K. Berriri.
- The numerical modeling of unilateral contact problems. For a realistic modeling of elastic waves propagation in the presence of cracks, it appears necessary to use unilateral contact conditions, such as Signorini's conditions, as boundary conditions along the crack. Such a problem remains essentially open from a mathematical point of view, and is very difficult numerically. With the thesis of G. Scarella, supported by a research contract with EDF, our main objective was to extend to this case the fictitious domain method initially designed for free boundaries (see [56], [51]).
- Complete models of musical instruments. This research theme is developed in collaboration with A. Chaigne (ENSTA) who is a specialist in musical acoustics. After the timpani (the thesis of L. Rhaouti defended in 1999) [59], we have been interested in the numerical simulation of the acoustic guitar (thesis of G. Derveaux [70], [16]). The difficulty of the problem lies in particular in the complexity of the underlying model which involves the coupling of wave equations in different dimensions and of different nature (e.g. the plate equation for the soundboard of the guitar). The solution we propose is a combination of the various techniques developed by our laboratory with the design of more specific tools (in this case the treatment of the sounboard, [15]).
- Reduced models for wind instruments. A 1D simplified model for "simple" wind instruments is given by the Loshkin's equation. In order to take into account visco-thermic losses at the wall, one must introduce additional terms, including fractional order derivatives, which makes the model more difficult. We have been able carry out the mathematical and numerical study of the complete model, for arbitrary geometries [75]. We aim now to consider non-linear terms characterizing brass instruments.

6.4. Time-harmonic diffraction problems

The mathematical analysis and numerical solution of time harmonic diffraction problems, set in unbounded domains, give rise to two types of difficulties.
Firstly, the boundary value problem (the PDE and the physical boundary conditions) has in general infinitely many solutions. Only one of them represents the physical time harmonic steady state solution. One has to characterize this so-called "outgoing" solution, by some radiation condition at infinity, and to derive a numerical method which is able to select it.
Secondly, time harmonic diffraction problems lead in general to non-coercive variational formulations, whose discretization by finite elements must be carefully written, in order to ensure stability and convergence. In addition, the resulting linear systems are quite difficult to solve.
Our contributions concern these both aspects.

- Higher-order volumic methods for time-harmonic wave equations. This is the subject of the PhD thesis of M. Durufle (see [62]) who is developing computational codes based on spectral elements for the time harmonic scalar wave equation and the Maxwell's system (in both 2D and 3D) with rather general boundary conditions (including generalized impedance conditions). The basic ingredient is the adaptation of the techniques previously developed in the time domain (see previous paragraph). Various techniques for unbounded domain have been implemented and compared (PML's, DtN maps, and coupling with integral equation techniques). Curved elements have also been implemented and particular attention has been paid to the relevant linear algebra (comparison of iterative methods, preconditionning,...). Some specific applications (optical filters in the framework of a contract with ATMEL, modeling of boundary layers or thin slots) have clearly shown the interest (if not the necessity) of using very high order methods.
- Time-harmonic aeroacoustics. This is a source of problems for which the choice of a good mathematical formulation (in view of its numerical approximation) is already a delicate question.

    i. First, we studied a scalar problem, corresponding to acoustic perturbations of a uniform flow in a 2D duct (thesis of L. Dahi and post-doc of S. Job). The scatterer is composed of one or several plates located in the duct aligned with the flow. The outgoing solution, including the vortex sheet downstream from the plate (determined via a Kutta condition), can be characterized by a limiting absorption technique, and computed numerically [41]. New results have been obtained for small Mach numbers (surprisingly, this case is the most difficult) and for two aligned plates, where the vortex sheet produced by the downstream edge of the first plate interacts with the second plate.

    ii. Then, we studied extensively a vector model (Galbrun's equation) which modelizes both acoustic and hydrodynamic perturbations of an arbitrary parallel flow (in which cases the equations can not be reduced to a scalar model - see the theses of G. Legendre and E.M. Duclairoir).
    The finite element discretization of the equation by Lagrange elements does not work, for reasons similar to the case of Maxwell's equations (this difficulty had been already noticed by several other french teams but, before the work of G. Legendre, no explanation or solution has ever been given to our knowledge). Due to this observation, we have developed a regularization technique, which consists of adding to the equation a relation satisfied by the curl of the solution, in order to recover the ellipticity of its stationnary part. This regularized formulation is of the Fredholm type and can be discretized by any H^1 conforming finite element method [46]. We aim now to extend these ideas to non-uniform flows [42].
    The last part of the research concerns the treatment of unbounded domains (see the section on absorbing boundary conditions and absorbing layers).

Finally, we have been involved in some non standard scattering problems in elastic wave propagation (in collaboration with A. Maurel (ESPCI)), namely the scattering of time-harmonic elastic waves by dislocations (typically micro-fractures at the scale of the atom). Such phenomena occur in non intrusive probe of materials: elastic waves can be used for measuring their fragility.

- We have considered the scattering of anti-plane shear waves by one screw dislocation and the scattering of in-plane shear and acoustic waves by one edge dislocation. The novelty of the problem is that the scatterer is vibrating, which leads to new questions of modelization and non standard physical phenomena (see [33]).
- In a second work, we have studied the coherent propagation of elastic waves through a (two dimensional) solid filled with randomly placed dislocations, both edge and screw, using a multiple scattering formalism. The wavelengths are supposed to be large compared to the size of the dislocations and dislocation density is supposed to be small. Our study concerns the determination of the coherent wavenumber, whose real part gives the effective wave velocity and imaginary part gives the attenuation length (or elastic mean free path) (see [34]).

6.5. Absorbing boundary conditions and absorbing layers

Wave propagation problems are very often posed in unbounded domains and one of the crucial questions for their numerical solution, in both the frequency domain and the time domain (the more difficult case), is to be able to bound artificially the computational domain. The works we have done on this subject can be divided into three categories:

- Exact boundary conditions. From the theoretical point of view, one can always write a transparent (or exact) boundary condition via the so-called Dirichlet to Neumann (DtN) maps. These operators are non local in space (and time for transient problems).
  - Time domain problems. For general boundaries, the DtN maps are not known explicitly but can be characterized through an integral equation (based on a representation of the solution by retarded potentials). The problem is then to find a way to discretize in a stable manner the coupling between such an integral equation and the interior equations. We are currently developing a stable algorithm based on the ideas used in vibro-acoustics (thesis of P. Grob). For certain geometries of the artificial boundaries, for instance a circle in 2D or a sphere in 3D, this Dirichlet to Neumann map is explicitly given as a convolution operator whose kernel appears as the sum of a series. One of the problems there is to find a way to compute this kernel efficiently (see [32]).
  - Frequency domain problems. We have been more specifically concerned with electromagnetic or elastic waveguides. The difficulty here is that the DtN like operators are not explicitly diagonalisable, contrary to the cases of the scalar wave equation or exterior problems. A good solution consists in working with quantities of mixed nature (in the sense that they mix data of “Dirichlet” or “Neumann” nature). One can then write explicit conditions whose analysis and numerical approximation raise some new difficulties:
    - Theoretically, the justification of the method requires the proof of the completeness of non standard (in particular non orthogonal) modal bases.
    - The variational formulation of the boundary value problem gives rise to non classical mixed formulations (that have been successfully implemented for Maxwell’s equations).

- Local absorbing boundary conditions. To reduce the cost due to the non local nature of the exact boundary conditions, one may use local approximations often called absorbing boundary conditions. Since the initial work of Engquist and Majda, a lot of work in the applied mathematics community has been devoted to the construction and analysis af such conditions for various types of equations. Our recent contributions in this area concern

    - a new look at the convergence analysis of higher order absorbing boundary conditions (when the order N goes to infinity). In [71], [72], for the simple half-space problem, we obtained new error estimates with the help of the Cagniard-De Hoop technique.
    - the design of absorbing boundary conditions for Galbrun's equations, which appears to be the source of new difficulties (instabilities for upstream boundaries). This work, part of the thesis of K. Berriri, is only at its beginning.

- Perfectly matched layers. An alternative to the use of transparent or absorbing boundary conditions consists in surrounding the computational domain by an artificial domain, called the absorbing layer, inside which the waves are damped. In 1994, Bérenger introduced the concept of Perfectly Matched Layers which have the astonishing property that no reflected wave is generated at the interface between the physical medium and the absorbing one. The first part of our works on PML's concerns time-domain problems:

    - We have contributed to the understanding of the stability properties of classical PML models, first for Maxwell's equations [50] (we give in particular some energy decays results - see also [54] for variants of usual PML's in electromagnetism), then for general hyperbolic systems [55] via Fourier analysis. We establish in particular a clear link between instability phenomena in PML's and the existence of so-called "back propagative waves" (notion which is linked to group velocities). This criterion permits to explain instability results for some anisotropic wave propagation models (in electromagnetism, in elasticity or acoustics in flows).
    - We have extended the "Zhao-Cangellaris" PML's for Maxwell's equations to elastic waves. This is of particular interest in order to use finite element methods (thesis of S. Fauqueux).
    - We have derived error estimates for PML's via the Cagniard De Hoop method (thesis of J. Diaz).
    - We have constructed stabilized PML's for anisotropic electromagnetism and for linearized Euler equations [73]. This last work is based on ideas which are similar to those developed independently by Hu.

  The second part concerns time harmonic problems in waveguides.

    - First we have considered the case of a 2D acoustic waveguide, in presence of a uniform subsonic flow. The absorbing layers are designed for the pressure field, satisfying the convected scalar Helmholtz equation. Comparing with an exact formulation with Dirichlet-to-Neumann maps on the artificial boundaries, we derived error estimates [14]: we proved in particular that, surprisingly, the so-called inverse upstream modes (the other name for back propagative modes), which become exponentially growing in the downstream layer, do not affect the efficiency of PMLs (contrary to time-domain applications). We also investigated a modified PML model, recently introduced for time dependent problems [73], which makes all outgoing waves evanescent. This model appears to be useful for the extension to the vector case of Galbrun's equation for which the analysis has been completely carried out.

- The extension to elastic waveguides is in progress, in collaboration with the Laboratoire d'Acoustique Ultrasonore et d'Electronique in Le Havre. This case is much more difficult, for both theoretical and numerical points of view, since there are no Dirichlet-to-Neumann maps for the displacement formulation. Numerical experiments show that PMLs work if there are no inverse modes. But in presence of inverse modes, the method does not select the correct outgoing solution of the diffraction problem [57].

6.6. Asymptotic methods and approximate models

Taking into account small perturbations or small scales in a given problem by direct numerical methods is often difficult (the method must be quite accurate) and costly. The typical example in wave propagation is the presence inside the computational domain of geometrical details whose dimensions are small with respect to the wavelength which a priori requires to use very thin meshes.

The development of approximate (or effective) models, which should be at the same time cheaper from the computational point of view and rich enough to take into account accurately the effect of the perturbation (or the small scale), offers a very interesting (if not necessary) alternative. This is also a very exciting challenge for an applied mathematician since it combines a step of modelization (the derivation of the approximate models is based on appropriate ansatz or heuristics), a step of mathematical analysis (justification of the model via stability results, convergence proofs and error estimates) and finally a step of numerical analysis (development of well suited numerical methods for the approximate problem) and validation.

Our first contributions in this area were concerning homogenized and thin layer models for electromagnetic waves in ferromagnetic media (see [76], [77], [78]) in the view of their application to stealth technology. During the last four years we have been working on various problems in the time harmonic regime:

- The modeling of thin slots. For the 2D problem, the typical difficulty is to couple an approximate 1D model inside the slot with the current 2D model through the two ends of the slot. We have first shown the soundness of a "brute" (but clever) 1D-2D coupling method (see [82]) and then developed a complete asymptotic analysis (the series of correctors are obtained via matched asymptotics expansions) that lead to approximate models of arbitrary accuracy (with respect to the width of the slot) which only require the resolution of a junction problem in a reference geometry (see [36]).
- The derivation of generalized impedance conditions for taking into account highly conducting (but not perfectly conducting) obstacles in electromagnetism (such conditions generalize the well known Leontovitch condition). We have derived an alternative approach (based on standard boundary layer approximations) to the use of local approximations of pseudo-differential operators (see for instance the works of H. Barucq and X. Antoine). This approach leads to optimal error estimates (see [25]) and very accurate numerical results (work under continuation).
- The modeling of the acoustic attenuation of exhaust mufflers including perforated duct (thesis of D. Drissi). As the hole diameter and the center-to-center distance between consecutive holes are supposed of same order, and small compared to the size of the muffler and the acoustic wavelength, an equivalent model for the perforated duct can be derived by using multiscale techniques and matched asymptotic expansions (see [13]).

6.7. Waveguides and resonances

The notion of guided waves and resonant modes, although clearly distinct, have in common to be associated with (possibly generalized) eigenvalue problems.
A waveguide is a cylindrical structure in which waves can propagate without any distorsion or attenuation along the invariance direction of the guide. Such waves are generally dispersive and their dispersion relation can be determined by solving self-adjoint eigenvalue problems. The guide is said to be closed if it is transversally bounded (this is the simplest situation). If the cross section is unbounded, one has an open waveguide, for which the presence of a continuum of radiating modes (these are not guided waves) makes all questions more difficult. In such a case, the confinement of the transverse energy of guided modes is due to physical mechanisms, that one can meet in the nature (water waves guided by a sloping beach, surface waves associated with earthquakes,...) or in various technological applications in electronics and optics (optical fibers, micro-components in integrated optics, micro-strip lines,...).
The study of "perfect" waveguides has been for a long time one of the main research topics of our team (see in particular [1] and the references therein). One of the main application concern the design of micro-components in integrated optics. We are now currently interested in non perfect waveguides (i.e. the structure is no longer perfectly cylindrical everywhere).

- The generalized mode matching method for the junction of open waveguides.
  During the thesis of Axel Tillequin, we have developped an original method for solving some 2D time harmonic diffraction problems. The method applies when the reference medium is stratified on each side of a straight interface Γ. We derived a coercive formulation of the problem set on Γ, by matching modal representations of the solution on each side of Γ. The difficulty and the originality come from the presence of continuous spectra in these representations. The problem has been applied successfully for simulating the abrupt junction between two open waveguides ([47][48]). Then it has been extended to periodically stratified media ([45]).
- Numerical techniques for non-uniform closed waveguides : we address here the question of designing efficient numerical methods in order to take into account smooth variations of closed waveguides. We have developped for this situation a hybrid method, called multi-modal technique, using modal decompositions in the transverse sections together with finite elements along the longitudinal axis of the waveguide. For an acoustic waveguide with a rigid boundary, we have shown that the natural modal basis produces a poor convergence, because of the presence of boundary layers at the boundary. Then we proved that the adjunction to the basis of one or more well-suited functions can significativly improve the convergence. Extension to the much more difficult case of elastic waveguides is in progress, with interesting applications to non-destructive testing.
  An alternative idea consists in the determination of the generalized impedance operator associated to each cross section of the waveguide. This operator depends on the abcissa along the waveguide. Using ideas from optimal control theory, it is possible to derive a Riccati differential equation for these operators (see [60] and the thesis of I. Champagne). From the mathematical point of view, the new difficulty lies in the fact that the unknown of this Ricatti equation is an unbounded operator.

Physically, resonance frequencies are the frequencies for which the response of a system (a medium, an obstacle,...) submitted to a periodic excitation presents a maximum. Thise quantities also allow us to determine the large time behaviour of corresponding evolution problems. Mathematically, they are either real eigenvalues of some frequency dependent selfadjoint operators or the complex poles of the meromorphic extension to complex frequencies of such operators (this corresponds to generalized eigenvalue problems). In the past years, the project has developped an expertise in the characterization and numerical calculation of resonance frequencies. Apart from the application of resonances to the singular expansion method (see the paragraph about time domain numerical methods), our more recent work on the subject concern some particular problems related to acoustics in flow:

- Resonances of an elastic plate in a confined flow. We have studied the real resonance frequencies of an elastic plate (of finite length) located in the middle of a straight duct. The plate interacts with a compressible fluid which moves, with a uniform subsonic velocity. For a fluid at rest or for a rigid plate, the problem can be written as a selfadjoint eigenvalue problem, and existence of resonances are obtained by using the Min-Max principle. The general case (fluid in flow and elastic plate) is more complicated and theoretical existence results of resonances are obtained only for small Mach numbers or very rigid plates. Theoretical results are illustrated by several numerical results, obtained with the code MELINA (see [43], [44]).

6.8. Imaging and inverse problems

Our contributions in this area have a recent history and have a special focus on inverse scattering problems encountered in electromagnetic or acoustic imaging. Generally speaking, these problems consists in determining (some informations on) the geometry and/or the location of an obstacle or an inhomogeneity from measured scattered fields.

Over the past decade a large amount of attention has been paid to a new class of methods that avoids the classic setting of these inverse problems as minimization problems. The linear sampling method constitutes one of the major methods that has emerged recently and offers a different view of these problems: the object is directly reconstructed from the spectral property of an operator associated with a given set of data. Our major contribution in the development of this method is the treatment of Maxwell equations [79], [68] and the realization of significant three dimensional inversions [67]. These contributions are summarized in the review article [69]. The extension of the method to the imaging of anisotropic inclusions has been also studied in the case of the Helmholtz equation [58] and Maxwell equations [24]. This method has shown to be very efficient when a large amount of data are available (for instance, one measures all around the obstacle the scattered field associated with incident waves coming from all directions). Hence the practical efficiency is very limited. This is why special efforts are now made to increase the accuracy of the method in the case of limited data and/or the coupling with other methods. This has led us to explore other type of methods that share the same spirit.

One possible approach is the method developed by Kusiak et Sylvester for determining the convex scattering support of an unknown scatterer, when its physical properties are not known. It consists in testing the range of special integral operators for a sampling set of test domains, using the far field pattern for one single incident wave. The method, initially developed in the free space, has been extended to 3D waveguides, for applications to acoustic imaging in a finite depth ocean. The main idea consists in considering each 2D problem satisfied by the projection of the scattered field on guided modes (Post Doc of S. Kusiak).

Another interesting imaging technique, based on the reciprocity gap principle, has been applied to the identification of planar cracks. This technique initially designed to solve the crack identification problem in the framework of electrostatic imaging has been extended to Helmholtz and Maxwell equations [12]. It requires in its principle the use of one measurement (one incident wave) at a fixed frequency but is restricted to particular problems such as the detection of point sources or the reconstruction of planar cracks. Combining ideas from the linear sampling method and this reciprocity gap technique allowed us to propose an new inversion scheme to solve the inverse problem of detecting buried objects [22].

We also made some contributions in the treatment of the imaging problem via iterative techniques. The first one concerns the detection of coated obstacles for which the theoretical foundation of a Gauss-Newton type method has been established [26]. The second one concerns the use of conformal mapping in electrostatic imaging (for the 2-d problems) where simply connected inclusion can be determined from iteratively solving a non linear differential equation (work in progress in collaboration with R. Kress).

Another of our contributions concerns time reversal acoustics, a method that has known in the last few years a significant growth of interest, covering a large number of applications (medical imaging, non destructive testing etc...)

The selective focusing obtained by iterating the time reversal process (D.O.R.T. method) has been satisfactorily explained for punctuals scatterers using Born approximation. In collaboration with K. Ramdani, we gave a mathematical justification of focusing in the more general context or arbitrary obstacles, sufficiently small and distant (compared to the wavelength). This analysis has been carried out for ideal time-reversal mirrors, able to reverse the far field of the scattered field (see [27]). We aim now to handel the real case, whith the mirror located at a finite distance of the obstacles (thesis of C. Ben Ammar).

7. Contracts and Grants with Industry

7.1. Contract ENSTA-DGA

This contract was about specific numerical methods for the simulation and optimal design of waveguides of variable cross-section.

7.2. Contract ENSTA-DGA

This contract concerns methods for real time computations for floating bodies subject to ocean swells, in view of the dynamic stabilization of platforms.

7.3. Contract INRIA-IFP

This contract has supported the PhD thesis of S. Fauqueux on the numerical simulation of elastic wave propagation in 2D and 3D anisotropic and heterogeneous media.

7.4. Contract INRIA-IFREMER

This contract was about numerical methods for underwater seismics.

7.5. Contract INRIA-EDF

This contract concerned the simulation of the diffraction of elastic waves by cracks modeled with unilateral contact conditions.

7.6. Contract INRIA-EDF

This contract concerned the development of space-time mesh refinement methods for the propagation of elastic waves and their coupling with the fictitious domain method.

7.7. Contract INRIA-CEA

This contract was about the direct resolution of Hamilton-Jacobi equations for the calculation of high frequency waves in the presence of caustics.

7.8. Contract INRIA-Schlumberger

This contract was about the numerical modeling of CHFR, a process used in the investigation of the subterrain with the help of low frequency electric currents.

7.9. Contract INRIA-ONERA Toulouse

This contract is about higher order methods (spectral elements and discontinuous Galerkin methods) for the resolution of Maxwell's equations.

7.10. Contract INRIA-EADS

This contract concerns the coupling of time domain integral equations with finite element methods with a view to the application to vibro-acoustics.

7.11. Contract INRIA-ONERA Palaiseau

The subject is the resolution of time harmonic Maxwell's equations with the help of higher order numerical methods.

7.12. Contract INRIA-ONERA-IEA-CEG

This contract consisted of submitting a detailed proposal (including theoretical arguments and numerical experiments) to implement major improvements in their electromagnetism code (our proposal is the one that has been retained).

7.13. Contract INRIA-IFREMER

About the numerical modelling by non conforming method of the sea-underground interface.

7.14. Contract INRIA-ATMEL

The subject was the accurate modelization of optical filters (Fabry-Perrot filters).

7.15. Contract INRIA-SHELL

This contract is about the numerical modeling of wave propagation in poro-elastic media.

8. Other Grants and Activities

8.1. Collaborations with other INRIA project-teams

- The project participates to the ARC HEADEXP (Realistic numerical modelling of human head tissues exposure to electromagnetic waves from mobile phones) which also involves the projects CAIMAN (S. Lanteri is coordinator of the ARC) and ODYSSEE from Sophia-Antipolis, and GAMMA from Rocquencourt.
- The project (J. Henry) has been participating to the project " Problèmes directs et inverses en EEG et MEG " on brain imaging, in the framework of the ACI Télémédecine, which also involes the projects ROBOTVIS (Sophia-Antipolis) and ESTIME (Rocquencourt).
- C. Hazard collaborates with K. Ramdani (Project CORIDA, INRIA Lorraine) on time reversal acoustics.
- The project has also close contacts with OTTO (J. D. Benamou, Rocquencourt) and some connections with GAMMA (Rocquencourt) as users of their mesh generators, MACS (Rocquencourt) for mechanical models of thin structures or SAGE (Rennes) on seismic modeling.

8.2. Collaborations with French research groups outside INRIA

- Participation in the GDR Ultrasons which groups 12 research laboratories (in Acoustics and Applied Mathematics) working on nondestructive testing.
- Collaborations with F. Collino (CERFACS, Toulouse) on various topics: local time stepping, PML's, domain decomposition,...
- Various collaborations with people at IRMAR (University of Rennes): singularities (M. Costabel, M. Dauge), electromagnetic waveguides (G. Caloz), MELINA (D. Martin), high frequency modeling (F. Castella).
- Collaboration with A. Maurel from ESPCI (Paris) on scattering by dislocations.
- Collaboration with F. Assous and J. Segré from CEA on time dependent Maxwell's equations.
- Collaboration with V. Pagneux (LAUM, University of Le Mans) on waveguide problems and aeroacoustics.

8.3. Collaborations with Foreign research groups

- The project has a long term collaboration with the University of Delaware (where two former PhD students of Ondes, O. Vacus and H. Haddar, have done their Post-Doc), in particular on the numerical analysis of wave equations (P. Monk) and on inverse scattering problems (F. Cakoni, D. Colton, P. Monk).
- The project has developed a collaboration with the LAMSIN from ENIT (Tunis) which includes time harmonic scattering problems, inverse scattering, time reversal,...
- The project has been participating in two projects of the Lyapunov Institute: one with A. Komech from Moscow University (he is a regular visitor of ONDES) on non linear waves, one with V. Tcheverda (Novosibirsk) in seismics.
- 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).
- We also have connections with the University of Santiago de Compostela (A. Bermúdez, D. Gómez, J. Rodríguez) and Stanford (Post-Docs of C. Tsogka and G. Derveaux in the group of G. Papanicolaou).
- We have recently developed new relationships with the British school of mathematics applied to wave problems (one workshop organized this year in Paris, one is planned for next year in England).
- E. Bécache collaborates with A. Kiselev (University of St Petersbourg) on surface waves in solids.
- P. Ciarlet has been collaborating with A. Buffa (Pavia) on the functional analysis of Maxwell's equations.
- P. Ciarlet and his students collaborate with J. Zou (Hong-Kong University) on the singular complement method.
- G. Cohen has initiated a collaboration with the University of Jyvaskyla (E. Heikkola) on piezoelectricity.
- H. Haddar collaborates with M. Piana (University of Genova) on the linear sampling method.
- H. Haddar collaborates with R. Kress (University of Goettingen) on inverse scattering and impedance tomography.
- C. Hazard develops a collaboration with M. Meylan (Auckland University, New Zealand) on the singularity expansion method.
- J. Henry has been collaborating with B. Louto (Lisbon University) in the framework of the franco-portuguese bilateral agreement INRIA - ICCTI.
- J. Henry has been collaborating with A. Ramos (University Complutense of Madrid) on the factorization of elliptic operators.
- J. Li collaborates with L. Greengard (Courant Institute) on fast integral equation methods for the wave and heat equations.
- The works of J. F. Mercier on dislocations are the subject of a collaboration with F. Lund (University of Chili, Santiago).

9. Dissemination

9.1. Visibility

- The project participates actively im the organization and composing a large part of the scientific committee of the International Conferences on Mathematical and Numerical Aspects of Wave Propagation (created in 1991 by G. Cohen and P. Joly). The most recent conference was WAVES2003 in Jyvaskyla (Finland) in July 2003. The next one will take place at Brown University (USA) in June 2003.
- The project organizes a monthly seminar, CRESPO. The seminar takes place alternatively at INRIA and ENSTA (changing each three months) and is composed of two talks each time.
- The project organizes regularly (about one edition each year) a series of INRIA workshops (high level courses for researchers and engineers) on wave propagation (Ecole des Ondes). These workshops are part of the CEA-EDF-INRIA summer school. The topics of the most recent workshops were:

  - Elastic Waves in solids, November 2001,
  - Direct and Inverse Problems in Diffraction Theory, January 2003,
  - Non linear processes in Quantum phenomena, January 2004.
- E. Bécache is member of the evaluation committee of INRIA.
- J.-D. Benamou was the head of the “ACI jeune chercheur” GO++ (2000-2002) which worked on the realisation of software library for the numerical solution of problems in geometrical optics.
- J.-D. Benamou co-organized with B. Engquist the workshop << Geometric high-frequency methods – applications to geophysics >>, *Institute for Pure and Applied Math, UCLA* April 2001.
- A.S. Bonnet-Ben Dhia and P. Joly are members of the Executive Committee of the GDR Ultrasons.
- A. S. Bonnet-Ben Dhia has been a member of the Comité National du CNRS (sections 09 et 41) during 2000-2002 and will be member of the Scientific Committee of the Department SPI of CNRS..
- P. Ciarlet coorganized, with P.A. Raviart and E. Sonnendrücker, the workshop *Numerical Simulation of charged particles* (Nancy, June 2001).
- P. Ciarlet coorganized a special day “Éléments finis vectoriels” at ENSTA (Paris, Février 2004).
- G. Cohen has published a book in the series “Scientific Computation”of Springer (see the list of references).
- J. Henry was the vice president of the Technical Committee 7 of IFIP and a member of the program committee of the Conference System Modeling and Optimization (Sophia Antipolis- July 2003).
- P. Joly is member of the Editorial Board of the Journal M2AN (Modélisation Mathématique et Analyse Numérique).
- P. Joly is member of the Editorial Board of the Book series “Scientific Computation” of Springer. (Modélisation Mathématique et Analyse Numérique).
- P. Joly was member of the CNU (Comité National des Universités (26th section for Applied Mathematics) during the period 1999-2003.
- P. Joly was the organizer of the day ILIAtech “Propagation des Ondes”, Rocquencourt, 29 Septembre 2003.
- P. Joly is a regular lecturer at Collège Polytechnique (Advanced courses for engineers who are working in industry).

- P. Joly was a member of the Scientific Committee of the Conference "World Congress on UltraSonics", Paris, 7-10 Septembre 2003. He organized the mini-symposium "Mathematical Methods in Imaging".
- P. Joly was invited as a plenary lecturer in the following Conferences:
  - Journées Européennes on Numerical Methods in Electromagnetics, Toulouse, March 2002.
  - SCEE (Scientific Computing in Electrical Engineering) 2002, Eindhoven, June 2002.
  - LMS Durham Symposium on Computational Methods for Wave Phenomena, Durham, July 2002.
  - CMMWP (Conference on Mathematical Modelling of Wave Phenomena), Vaxjö, November 2002.
  - Colloque National d'Analyse Numérique, La Grande Motte, June 2003.
  - Spring Meeting of the Swiss Mathematical Society, Bâle, June 2003.
  - Futures directions in Applied Mathematics, Conference in the honor of honneur de J. C. Nédélec, Paris, June 2003.
  - DDM15 15th International Conference on Domain Decomposition Methods, Berlin, July 2003.
- J. F. Mercier and A. S. Bonnet-Ben Dhia have organized, in collaboration with C. Linton, the workshop Mathmondes (a French-British worshop on Mathematical Techniques for Wave Problems), ENSTA (Paris, June 2004).

9.2. Teaching

All members of Project ONDES, 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:

- *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)
- *Jacques Henry*
  Ecole Des Mines de Paris (undergraduate course)
- *Houssem Haddar*
  Ecole Supérieure d'Ingénieurs Léonard de Vinci
- *Patrick Joly*
  Ecole Polytechnique (2nd and 3rd years)
  ENSTA (graduate courses)
  ENIT (Master of applied mathematics)
  Université de Bordeaux I (DEA of applied mathematics)
  Université of Santiago (DEA of applied mathematics)
- *Marc Lenoir*
  ENSTA (graduate course)
  ENS Cachan (Preparation to agrégation)
  Université de Versailles-Saint Quentin (DEA of Mathematics and Physics)
- *Eric Lunéville*
  ENSTA (graduate and postgraduate courses)
- *Jean-François Mercier*
  ENSTA (postgraduate course)

9.3. Scientific Videos

The project works in collaboration with the Service Audiovisuel of INRIA Rocquencourt in the making of scientific videos:

- Auteur(s) scientifique(s): Joly, Patrick / Rodriguez, Jeronimo Raffinement de maillage espace-temps pour les équations de Maxwell, réalisation : Paouri, Arghyro, 2001, 5 mn10
- Auteur(s) scientifique(s): Bécache, Éliane / Chaigne, Antoine / Derveaux, Grégoire / Joly, Patrick Modélisation numérique de la guitare, réalisation : Paouri, Arghyro, 2001, 3 mn 56
- Auteur(s) scientifique(s) : Fauqueux, Sandrine / Joly, Patrick Couches P.M.L. en électromagnétisme anisotrope, réalisation : Paouri, Arghyro, 2001, 1 mn
- Auteur(s) scientifique(s) : Joly, Patrick / Scarella, Gilles Propagation d'ondes avec condition de contact unilatéral : simulation monodimensionnelle, réalisation : Paouri, Arghyro, 2001, 5 mn 58
- Auteur(s) scientifique(s) : Derveaux, Grégoire Modélisation numérique de la guitare (v. soutenance de thèse), Réalisation : Paouri, Arghyro, 2002, 4 mn 52
- Auteur(s) scientifique(s) : Joly, Patrick / Rodriguez, Jeronimo Space-Time Mesh Refinement for Maxwell's Equations, Réalisation : Paouri, Arghyro, 2002, 5 mn 10
- Auteur(s) scientifique(s) : Joly, Patrick Some scientific achievements 1996 - 2001 Projet Ondes, Réalisation : Paouri, Arghyro, 2002, 9 mn 25
- Auteur(s) scientifique(s) : Joly, Patrick Visiting Committee Presentation Jan. 14, 2002, Réalisation : Paouri, Arghyro, 2002, 7 mn 18
- Auteur(s) scientifique(s) : Joly, Patrick / Rodriguez, Jeronimo Raffinement de maillage espace-temps pour les équations de Maxwell,Réalisation : Paouri, Arghyro, fin 2001, 5 mn10

10. Bibliography

Major publications by the team in recent years

[1] A. S. Bonnet-Ben Dhia, P. Joly. *Mathematical Analysis and Numerical Approximation of Optical Waveguides*, chap. 8, Gang Bao and Lawrence Cowsar and Wen Masters, SIAM Frontiers book series in Applied Mathematics, 2001, p. 273-324.

[2] G. C. Cohen. *Higher-Order Numerical Methods for Transient Wave Equations*, Springer, 2001.

[3] C. Hazard, M. Lenoir. *Surface Water Waves*, chap. 2, E.R. Pike and P.C. Sabatier, Academic Press, 2001.

Doctoral dissertations and Habilitation theses

[4] I. Champagne. *Méthodes de Factorisation des Equations aux Dérivées Partielles*, Ph. D. Thesis, Ecole Polytechnique, 2004.

[5] J. Diaz. *Couches absorbantes parfaitement adaptées, acoustique en écoulement et interaction fluide-structure: une étude analytique et numérique*, Ph. D. Thesis, Université Paris 6, 2004.

[6] A. Ezziani. *Modélisation mathématique et numérique de la propagation d'ondes dans les milieux viscoélastiques linéaires et poroélastiques*, Ph. D. Thesis, Université Paris 9, 2004.

[7] F. Loret. *Décomposition sur les mouvements périodiques ou sur les modes résonants pour la simulation de la transitoire d'un problème de tenue à la mer*, Ph. D. Thesis, Ecole Centrale Paris, September 2004.

[8] S. Pernet. *Méthodes numériques d' ordre élevé pour les équations de Maxwell*, Ph. D. Thesis, Université Paris IX Dauphine, November 2004.

[9] J. Rodríguez. *Raffinement de Maillage Spatio-Temporel pour les Équations de l'Élastodynamique*, Ph. D. Thesis, Université Paris IX Dauphine, December 2004.

[10] G. Scarella. *Etude théorique et Numérique de la propagation d'ondes en présence de contact unilaéral dans un domaine fissuré*, Ph. D. Thesis, Université Paris IX Dauphine, March 2004.

[11] S. Tordeux. *Méthodes Asymptotiques pour la Propagation des Ondes dans les Milieux comportant des Fentes*, Ph. D. Thesis, Université de Versailles, december 2004.

Articles in referred journals and book chapters

[12] A. B. Abda, F. Delbary, H. Haddar. *On the use of the reciprocity gap principle in inverse scattering from planar cracks*, in "Mathematical Models and Methods in the Applied Science", soumis.

[13] A. S. Bonnet-Ben Dhia, D. Drissi, N. Gmati. *Simulation of muffler's transmission losses by a homogenized finite element method.*, in "Journal of Computational Acoustics", vol. 12, 2004.

[14] E. BÉCACHE, A.-S. BONNET-BEN DHIA, G. LEGENDRE. *Perfectly matched layers for the convected Helmholtz equation*, in "SIAM J. Numer. Anal.", vol. 42, 2004, p. 409 - 433.

[15] E. BÉCACHE, G. DERVEAUX, P. JOLY. *An efficient numerical method for the resolution of the Kirchhoff-Love dynamic pale equation*, in "Numerical Methods for Partial Differential Equations", to appear.

[16] E. BÉCACHE, G. DERVEAUX, P. JOLY. *Numerical Simulation of a guitar*, in "Computers and Structures", to appear.

[17] E. BÉCACHE, P. JOLY, A. EZZIANI. *A mixed finite element approach for viscoelastic wave propagation*, in "Computational Geosciences", to appear.

[18] E. BÉCACHE, P. JOLY, J. RODRÍGUEZ. *Space-Time Mesh Refinement for Elastodynamics. Numerical Results*, in "J. Comp. Meth. Appl. Mech. Eng.", 2004.

[19] P. CIARLET, P. CIARLET JR. *Another approach to linearized elasticity and Korn's inequality*, in "C. R. Acad. Sci. Paris, Ser. I.", 2004.

[20] P. CIARLET JR. *Augmented formulations for solving Maxwell equations*, in "Comput. Methods Appl. Mech. Engrg.", 2004.

[21] F. COLLINO, T. FOUQUET, P. JOLY. *Conservative space-time mesh refinement methods for 3D Maxwell's equations*, in "J. of Comp. Physics", n^o 2, submitted.

[22] D. COLTON, H. HADDAR. *An Application of the Reciprocity Gap Functional to Electromagnetic Inverse Scattering Theory*, in "??", soumis.

[23] J. DIAZ, P. JOLY. *Robust high order non conforming finite element formulation for time domain fluid-structure interaction*, to appear in J. of Comp. Acoustics.

[24] H. HADDAR. *The interior transmission problem for anisotropic Maxwell's equations and its applications to the inverse problem*, in "Math. Meth. Appl. Sci.", 2004.

[25] H. HADDAR, P. JOLY, H. NGUYEN. *Asymptotic Models for Scattering from Strongly Absorbing Obstacles: the Scalar Case*, in "M3AS", submitted.

[26] H. HADDAR, R. KRESS. *On the Fréchet derivative for Obstacle Scattering with an Impedance Boundary Condition*, in "Siam J. Appl. Math.", 2004.

[27] C. HAZARD, K. RAMDANI. *Selective acoustic focusing using time-harmonic reversal mirrors*, in "SIAM J. Appl. Math.", 2004.

[28] 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.

[29] P. JOLY, J. RODRÍGUEZ. *An Error Analysis of Conservative Space-Time Mesh Refinement Methods for the 1D Wave Equation*, in "SIAM J. on Num. Anal.", To appear.

[30] J. LI, L. GREENGARD. *High order marching schemes for the wave equation in complex geometry*, in "Journal of Computational Physics", 2004.

[31] J. LI, L. GREENGARD. *Low rank solution of Lyapunov equations*, in "SIAM Review", 2004.

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

[33] A. MAUREL, J. MERCIER, F. LUND. *Elastic wave propagation through a random array of dislocations*, in "Phys. Rev. B", 2004.

[34] A. MAUREL, J. MERCIER, F. LUND. *Scattering of an elastic wave by a single dislocation*, in "J. Acoust. Soc. Am.", 2004.

[35] J. RODRÍGUEZ. *Une Nouvelle Méthode de Raffinement de Maillage Spatio-Temporel pour l'Équation des Ondes*, in "C. R. Acad. Sci. Paris Sér. I Math.", 2004.

[36] S. TORDEUX, P. JOLY. *An asymptotic analysis of time harmonic waves in media with thin slots*, in "SIAM Journal on Mathematical Analysis", to appear.

Publications in Conferences and Workshops

[37] S. GUGERCIN, J. LI. *Smith-Type methods for balanced truncation of large sparse systems*, in "Proceedings of the Oberwolfach mini-workshop on dimension reduction", Lecture Notes on Computational Science and Engineering, 2004.

[38] P. JOLY, J. RODRÍGUEZ. *A New Space-Time Mesh Refinement Method for Elastodynamics*, in "4th European Congress on Computational Methods in Applied Sciences and Engineering", 2004.

[39] M. MEYLAN, C. HAZARD, F. LORET. *Linear time-dependent motion of a two-dimensional floating elastic plate in finite depth water using the Laplace transform*, in "19th International Workshop on Water Waves and Floating Bodies", 2004.

Bibliography in notes

[40] F. ASSOUS, P. CIARLET, JR, S. LABRUNIE, J. SEGRÉ. *Numerical solution to the time-dependent Maxwell equations in axisymmetric singular domains: The Singular Complement Method*, in "J. Comput. Phys.", vol. 191, 2003, p. 147-176.

[41] A. S. BONNET-BEN DHIA, L. DAHI, E. LUNÉVILLE, V. PAGNEUX. *Acoustic diffraction by a rigid plate in a uniform flow*, in "Mathematical Models and Methods in Applied Sciences", vol. 12, 2002, p. 625-647.

[42] A. S. BONNET-BEN DHIA, G. LEGENDRE, E. LUNÉVILLE. *Regularization of the Time-Harmonic Galbrun's Equations*, in "Mathematical and Numerical Aspects of Wave Propagation.", G. C. COHEN, E. HEIKKOLA,

P. JOLY, P. NEITTAANMÄKI (editors)., Springer, 2003, p. 78–83.

[43] A. BONNET-BEN DHIA, J. MERCIER. *Résonances d'une plaque élastique dans un conduit en présence d'écoulement*, in "AMRTMA (Acoustics, Mechanics, and the Related Topics of Mathematical Analysis)", A. WIRGIN (editor)., World Scientifi, 2002.

[44] A. S. BONNET-BEN DHIA, J. F. MERCIER. *Resonances of an Elastic Plate in a Confined Flow*, in "Mathematical and Numerical Aspects of Wave Propagation", G. C. COHEN, E. HEIKKOLA, P. JOLY, P. NEITTAANMÄKI (editors)., Springer, 2003, p. 836–841.

[45] A. S. BONNET-BEN DHIA, K. RAMDANI. *Diffraction by an acoustic grating perturbed by a bounded obstacle*, in "Modeling and Computation of Optics and Electromagnetics, Special Issue, Advances in Computational Mathematics", vol. 16, n° 2-3, 2002, p. 113-138.

[46] A.-S. BONNET-BEN DHIA, G. LEGENDRE, E. LUNÉVILLE. *Analyse mathématique de l'équation de Galbrun en écoulement uniforme*, in "Comptes-Rendus de l'Académie des Sciences", vol. Tome 329, 2001, p. 601–606.

[47] A.-S. BONNET-BEN DHIA, A. TILLEQUIN. *A generalized mode matching method for scattering problems with unbounded obstacles*, in "Journal of Computational Acoustics", vol. 9, 2001, p. 1611 - 1631.

[48] A.-S. BONNET-BEN DHIA, A. TILLEQUIN. *A limiting absorption principle for scattering problems with unb ounded obstacles*, in "Mathematical Methods in the Applied Sciences", vol. 24, 2001, p. 1089–1111.

[49] E. BÉCACHE, A. EZZIANI, P. JOLY. *Modeling of wave propagation in linear viscoelastic media*, in "Mathematical Modelling of Wave Phenomena", vol. 7, Mathematical modelling in physics, engineering and cognitive sciences, 2003.

[50] E. BÉCACHE, P. JOLY. *On the analysis of Bérenger's Perfectly Matched Layers for Maxwell's equations*, in "M2AN", vol. 36, n° 1, 2002, p. 87-120.

[51] E. BÉCACHE, P. JOLY, G. SCARELLA. *A fictitious domain method for a unilateral contact problem*, in "Mathematical and Numerical Aspects of Wave Propagation", G. C. COHEN, E. HEIKKOLA, P. JOLY, P. NEITTAANMÄKI (editors)., Springer-Verlag, 2003, p. 431-436.

[52] E. BÉCACHE, P. JOLY, C. TSOGKA. *Fictitious domains, mixed finite elements and perfectly matched layers for 2D elastic wave propagation*, in "J. of Comp. Acoustics", vol. 9, n° 3, September 2001, p. 1175–1203.

[53] E. BÉCACHE, P. JOLY, C. TSOGKA. *A new family of mixed finite elements for the linear elastodynamic problem*, in "SIAM J. on Num. Anal.", vol. 39, n° 6, 2002, p. 2109-2132.

[54] E. BÉCACHE, P. PETROPOULOS, S. GEDNEY. *On the long-time behavior of unsplit Perfectly Matched Layers*, Technical report, n° RR-4538, INRIA, 2002, http://www.inria.fr/rrrt/rr-4538.html.

[55] E. BÉCACHE, S. FAUQUEUX, P. JOLY. *Stability of perfectly matched layers, group velocities and anisotropic waves*, in "J. Comput. Phys.", vol. 188, n° 2, 2003, p. 399–433.

[56] E. BÉCACHE, P. JOLY, G. SCARELLA. *A fictitious domain method for unilateral contact problems in non destructive testing*, in "Computational and Fluid ans Solid Mechanics", ELSEVIER (editor)., 2001, p. 65-67.

[57] E. BÉCACHE, A.-S. BONNET BEN DHIA. *PMLs for the numerical simulation of harmonic diffracted waves in an elastic plate.*, in "Proceedings of the World Congress on Ultrasonics, Paris", 2003, p. 1019-1022, http://www.sfa.asso.fr/wcu2003/.

[58] F. CAKONI, D. COLTON, H. HADDAR. *The Linear Sampling Method for Anisotropic Media*, in "J. Comp. and Appl. Math.", vol. 146, n^o 2, 2002, p. 285-299.

[59] A. CHAIGNE, P. JOLY, L. RHAOUTI. *Le son des timbaless*, in "Pour la Sciences, Ser. I", n^o 287, 2001.

[60] I. CHAMPAGNE, J. HENRY. *Riccati equation for the impedance of waveguides*, in "Mathematical and Numerical Aspects of Wave Propagation", G. C. COHEN, E. HEIKKOLA, P. JOLY, P. NEITTAANMÄKI (editors)., Springer, 2003, p. 457–462.

[61] P. CIARLET, JR, J. HE. *The Singular Complement Method for 2d problems*, in "C. R. Acad. Sci. Paris, Ser. I", vol. 336, 2003, p. 353-358.

[62] G. COHEN, M. DURUFLÉ. *Mixed Spectral Elements for the Helmholtz Equation*, in "Proceedings of the Sixth International Conference on Mathematical and Numerical Aspects of Wave Propagation. Jyvaskyla, Finland.", G. C. COHEN, E. HEIKKOLA, P. JOLY, P. NEITTAANMÄKI (editors)., Springer-Verlag, 2003, p. 743–748.

[63] G. C. COHEN, S. FAUQUEUX. *3D elastic modeling with mass-lumped mixed finite elements*, in "Proc. of the 64th EAGE Conference & Exhibition, 27-30 mai 2002, Florence", 2002.

[64] G. COHEN, S. FAUQUEUX. *Mixed Spectral Elements for the Linear Elasticity System in Unbounded Domains*, in "Proceedings of the Sixth International Conference on Mathematical and Numerical Aspects of Wave Propagation. Jyvaskyla, Finland.", G. C. COHEN, E. HEIKKOLA, P. JOLY, P. NEITTAANMÄKI (editors)., Springer-Verlag, 2003, p. 363–368.

[65] F. COLLINO, T. FOUQUET, P. JOLY. *A conservative space-time mesh refinement method for the 1-D wave equation. II. Analysis*, in "Numer. Math.", vol. 95, n^o 2, 2003, p. 223–251.

[66] F. COLLINO, T. FOUQUET, P. JOLY. *A conservative space-time mesh refinement method for the 1-D wave equation. I. Construction*, in "Numer. Math.", vol. 95, n^o 2, 2003, p. 197–221.

[67] F. COLLINO, M. B. FARES, H. HADDAR. *Numerical and analytical studies of the linear sampling method in electromagnetic inverse scattering problems*, in "Inverse Problems", vol. 19, 2003, p. 1279-1298.

[68] D. COLTON, H. HADDAR, P. MONK. *The Linear Sampling Method for Solving the Electromagnetic Inverse Scattering Problem*, in "SIAM J. Sci. Comp.", vol. 24, n^o 3, 2002, p. 719-731.

[69] D. COLTON, H. HADDAR, M. PIANA. *The linear sampling method in inverse electromagnetic scattering theory*, in "Inverse Problems", vol. 19, 2003, p. 105–137.

[70] G. DERVEAUX, A. CHAIGNE, P. JOLY, E. BÉCACHE. *Time-domain simulation of a guitar : model and method*, in "J. Acoust. Soc. Am.", vol. 114, n^o 6, 2003, p. 3368 - 3383.

[71] J. DIAZ, P. JOLY. *An Analysis of Higher Order Boundary Conditions for the Wave Equation.*, in "SIAM J. on Applied Mathematics", to appear.

[72] J. DIAZ, P. JOLY. *An Analysis of Higher Order Boundary Conditions for the Wave Equation.*, Technical report, n^o RR-4962, INRIA, 2003, http://www.inria.fr/rrrt/rr-4962.html.

[73] J. DIAZ, P. JOLY. *Stabilized Perfectly Matched Layer for Advective Acoustics*, in "Mathematical and Numerical Aspects of Wave Propagation", G. C. COHEN, E. HEIKKOLA, P. JOLY, P. NEITTAANMÄKI (editors)., Springer, 2003, p. 115-119.

[74] E. GARCIA. *Résolution des équations de Maxwell instationnaires avec charges dans des domaines non convexes*, Ph. D. Thesis, Université Pierre et Marie Curie, Paris, 2002.

[75] H. HADDAR, T. HÉLIE, D. MATIGNON. *A Webster-Lokshin model for waves with viscothermal losses and impedance boundary conditions: strong solutions*, in "Mathematical and numerical of wave propagation", G. C. COHEN, E. HEIKKOLA, P. JOLY, P. NEITTAANMÄKI (editors)., Springer, 2003, p. 66-71.

[76] H. HADDAR, P. JOLY. *Effective Boundary Conditions for Thin Ferromagnetic Coatings. Asymptotic Analysis of the 1D Model*, in "Asymptotic Analysis", 2001.

[77] H. HADDAR, P. JOLY. *Stability of Thin Layer Approximation of Electromagnetic Waves Scattering by Linear and Non Linear Coatings*, in "J. Comp. and Appl. Math.", vol. 143, n^o 2, 2002, p. 201-236.

[78] H. HADDAR, P. JOLY. *Homogenized model for a laminar ferromagnetic medium*, in "Proc. Roy. Soc. Edinburgh Sect. A", vol. 133, n^o 3, 2003, p. 567–598.

[79] H. HADDAR, P. MONK. *The Linear Sampling Method for Solving the Electromagnetic Inverse Medium Problem*, in "Inverse Problems", vol. 18, 2002, p. 891-906.

[80] C. HAZARD. *Mémoire d'Habilitation à Diriger les Recherches : Analyse moda le de la propagation des ondes*, Ph. D. Thesis, Université Paris 6, Paris, 2001.

[81] P. JOLY. *Topics in Computational Wave Propagation: Direct and Inverse Problems.*, Lecture notes in computational science and engineering, chap. Variational methods for time-dependent wave propagation problems., n^o 31, Springer, 2003, p. 201–264.

[82] P. JOLY, M. LENOIR, S. TORDEUX. *Asymptotical Models for Wave Propagation in Media Including Slots*, in "Mathematical and Numerical Aspects of Wave Propagation", G. C. COHEN, E. HEIKKOLA, P. JOLY, P. NEITTAANMÄKI (editors)., Springer, 2003, p. 169-173.