IN PARTNERSHIP WITH:
CNRS

Ecole nationale supérieure des techniques avancées

Activity Report 2015

Project-Team POEMS

Wave propagation: mathematical analysis and simulation

RESEARCH CENTER
Saclay - Île-de-France

THEME
Numerical schemes and simulations

Table of contents

Project-Team POEMS

Creation of the Project-Team: 2005 January 01

Keywords:

Computer Science and Digital Science:

6.1.1. - Continuous Modeling (PDE, ODE)
6.1.4. - Multiscale modeling
6.1.5. - Multiphysics modeling
6.2.1. - Numerical analysis of PDE and ODE
6.2.7. - High performance computing
6.3.1. - Inverse problems

Other Research Topics and Application Domains:

4.1. - Fossile energy production
5.3. - Nanotechnology and Biotechnology
5.4. - Microelectronics
9.4.2. - Mathematics
9.4.3. - Physics

1. Members

Research Scientists

Anne-Sophie Bonnet-Ben Dhia [Team leader, CNRS, Senior Researcher, HdR]
Patrick Joly [Previous team leader, Inria, Senior Researcher, HdR]
Marc Bonnet [CNRS, Senior Researcher, HdR]
Eliane Bécache [Inria, Researcher, HdR]
Stéphanie Chaillat [CNRS, Researcher]
Gary Cohen [Inria, Researcher, HdR]
Christophe Hazard [CNRS, Researcher, HdR]
Jean-François Mercier [CNRS, Researcher, HdR]

Faculty Members

Marc Lenoir [ENSTA, Professor, HdR]
Laurent Bourgeois [ENSTA, Professor, HdR]
Patrick Ciarlet [ENSTA, Professor, HdR]
Sonia Fliss [ENSTA, Associate Professor]
Eric Lunéville [ENSTA, Professor]

Engineers

Nicolas Kielbasiewicz [CNRS, Engineer]
Colin Chambeyron [CNRS, Engineer]
Christophe Mathulik [ENSTA, Engineer]

PhD Students

Zouhair Adnani [from Dec 2014]
Marc Bakry
Geoffrey Beck
Antoine Bensalah
Camille Carvalho

Mathieu Chamaillard
Rémi Cornaggia
Luca Desiderio
Léandre Giret
Matthieu Lecouvez
Simon Marmorat
Laure Pesudo [from Oct 2014]
Arnaud Recoquillay [from Oct 2014]
Antoine Tonnoir
Elizaveta Vasilevskaya
Audrey Vigneron [until Jan 2015]
Valentin Vinoles
Emmanuel Zerbib

Post-Doctoral Fellows
Maryna Kachanovska
Christian Stohrer [until Sep 2015]
Khac Long Nguyen [until Sep 2015]
Samuel Groth
Nicolas Salles

Visiting Scientists
Nabil Gmati [from Mar to Jun 2015]
Sergei Nazarov [from Jun to Oct 2015]
Shravan Veerapaneni [Dec 2015]
Maxence Cassier [from Apr to Jun 2015]
Martin Halla [Jun 2015]

Administrative Assistants
Myriam Brettes [Min. de l'Intérieur, until Aug 2015]
Katia Evrat [Inria]

Other
Bérangère Delourme [Univ. Paris XIII, Associate Professor]

2. Overall Objectives

2.1. The topic of waves

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 scales of the universe (electromagnetic waves, gravity waves) and of the atoms (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 various domains of physics and engineering sciences.

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.

2.2. POEMS activities

The project POEMS is an UMR (Unité Mixte de Recherche) between CNRS, ENSTA ParisTech and Inria (UMR 7231). The general activity of the project is oriented toward the design, the analysis, the numerical approximation and the control of mathematical models for the description of wave propagation in mechanics, physics and engineering sciences.

Beyond the general objective of contributing to the progress of the scientific knowledge, four goals can be ascribed to the project:

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

3. Research Program

3.1. General description

Our activity relies on the existence of boundary value problems established by physicists to model the propagation of waves in various situations. The basic ingredient is a linear partial differential equation of the hyperbolic type, whose prototype is the wave equation (or the Helmholtz equation if time-periodic solutions are considered). Nowadays, the numerical techniques for solving the basic academic problems are well mastered. However, the solution of complex wave propagation problems close to real applications still raises (essentially open) problems which constitute a real challenge for applied mathematicians. In particular, several difficulties arise when extending the results and the methods from the scalar wave equation to vectorial problems modeling wave propagation in electromagnetism or elastodynamics.

A large part of research in mathematics, when applied to wave propagation problems, is oriented towards the following goals:

- The design of new numerical methods, increasingly accurate and efficient.
- The development of artificial transparent boundary conditions for handling unbounded propagation domains.
- The treatment of more and more complex configurations (non local models, non linear models, coupled systems, periodic media).
- The study of specific phenomena such as guided waves and resonances, which raise mathematical questions of spectral theory.
- The development of approximate models via asymptotic analysis with multiple scales (thin layers, boundary layers effects, small homogeneities, homogenization, ...).
- The development and the analysis of algorithms for inverse problems (in particular for inverse scattering problems) and imaging techniques, using data from wave phenomena.

3.2. Wave propagation in non classical media

Extraordinary phenomena regarding the propagation of electromagnetic or acoustic waves appear in materials which have non classical properties: materials with a complex periodic microstructure that behave as materials with negative physical parameters, metals with a negative dielectric permittivity at optical frequencies, magnetized plasmas endowed with a strongly anisotropic and sign-indefinite permittivity tensor. These non classical materials raise original questions from theoretical and numerical points of view.

The objective is to study the well-posedness in this unusual context where physical parameters are sign-changing. New functional frameworks must be introduced, due, for instance, to hypersingularities of the electromagnetic field which appear at corners of metamaterials. This has of course numerical counterparts. In particular, classical Perfectly Matched Layers are unstable in these dispersive media, and new approaches must be developed.

Two ANR projects (METAMATH and CHROME) are related to this activity.

3.3. Wave propagation in heterogeneous media

Our objective is to develop efficient numerical approaches for the propagation of waves in heterogeneous media.

We aim on one hand to improve homogenized modeling of periodic media, by deriving enriched boundary conditions (or transmission conditions if the periodic structure is embedded in a homogeneous matrix) which take into account the boundary layer phenomena.

On the other hand, we like to develop multi-scale numerical methods when the assumption of periodicity on the spatial distribution of the heterogeneities is relaxed, or even completely lost. The general idea consists in a coupling between a macroscopic solver, based on a coarse mesh, with some microscopic representation of the field. This latter can be obtained by a numerical microscopic solver or by an analytical asymptotic expansion. This leads to two very different approaches which may be relevant for very different applications.

3.4. Spectral theory and modal approaches for waveguides

The study of waveguides is a longstanding and major topic of the team. Concerning the selfadjoint spectral theory for open waveguides, we turned recently to the very important case of periodic media. One objective is to design periodic structures with localized perturbations to create gaps in the spectrum, containing isolating eigenvalues.

Then, we would like to go further in proving the absence of localized modes in non uniform open waveguides. An original approach has been successfully applied to the scalar problem of a 2D junction. The challenge now is to extend these ideas to other configurations: 3D junctions, bent waveguides, vectorial problems...

Besides, we will continue our activity on modal methods for closed waveguides. In particular, we aim at extending the enriched modal method to take into account curvature and rough boundaries.

Finally, we are developing asymptotic models for networks of thin waveguides which arise in several applications (electric networks, simulation of lung, nanophotonics...).

3.5. Inverse problems

Building on the strong expertise of POEMS in the mathematical modeling of waves, most of our contributions aim at improving inverse scattering methodologies.

We acquired some expertise on the so called Linear Sampling Method, from both the theoretical and the practical points of view. Besides, we are working on topological derivative methods, which exploit small-defect asymptotics of misfit functionals and can thus be viewed as an alternative sampling approach, which can take benefit of our expertise on asymptotic methods.

An originality of our activity is to consider inverse scattering in waveguides (the inverse scattering community generally considers only free-space configurations). This is motivated at the same time by specific issues concerning the ill-posedness of the identification process and by applications to non-destructive techniques, for waveguide configurations (cables, pipes, plates etc...).

Lastly, we continue our work on the so-called exterior approach for solving inverse obstacle problems, which associates quasi-reversibility and level set methods. The objective is now to extend it to evolution problems.

3.6. Integral equations

Our activity in this field aims at developing accurate and fast methods for 3D problems.

On one hand, we developed a systematic approach to the analytical evaluation of singular integrals, which arise in the computation of the matrices of integral equations when two elements of the mesh are either touching each other or geometrically close.

On the other hand, POEMS is developing Fast Boundary Element Methods for 3D acoustics or elastodynamics, with applications to soil-structure interaction, seismology or seismic imaging.

Finally, a posteriori error analysis methodologies and adaptivity for boundary integral equation formulations of acoustic, electromagnetic and elastic wave propagation is investigated in the framework of the ANR project RAFFINE.

3.7. Domain decomposition methods

This is a come back to a topic in which POEMS contributed in the 1990's. It is motivated by our collaborations with the CEA-CESTA and the CEA-LIST, for the solution of large problems in time-harmonic electromagnetism and elastodynamics.

We combine in an original manner classical ideas of Domain Decomposition Methods with the specific formulations that we use for wave problems in unbounded domains, taking benefit of the available analytical representations of the solution (integral representation, modal expansion etc...).

4. Application Domains

4.1. Acoustics

Two particular subjects have retained our attention recently.

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

Musical acoustics constitutes a particularly attractive application. We are concerned by the simulation of musical instruments. The objective is both a better understanding of the behavior of existing instruments and an aid for the manufacturing of new instruments. We have successively considered the timpani, the guitar and the piano. This activity is continuing in the framework of the European Project BATWOMAN.

4.2. Electromagnetism

Applied mathematics for electromagnetism during the last ten years have mainly concerned stealth technology and electromagnetic compatibility. These areas are still motivating research in computational sciences (large scale computation) and mathematical modeling (derivation of simplified models for multiscale problems). These topics are developed in collaboration with CEA, DGA and ONERA.

Electromagnetic propagation in non classical media opens a wide and unexplored field of research in applied mathematics. This is the case of wave propagation in photonic crystals, metamaterials or magnetized plasmas. Two ANR projects (METAMATH and CHROME) support this research.

Other subjects are motivated by our partnership with CEA-LIST concerning the simulation of non-destructive testing methods: the development of asymptotic models for complex electromagnetic networks and the simulation by integral equations of eddy current phenomena.

4.3. 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. A major application topic has emerged during the past years : the non destructive testing by ultra-sounds which is the main topic of our collaboration with CEA-LIST. On the other hand, we are developing efficient integral equation modelling for geophysical and civil engineering applications (soil-structure interaction for civil engineering, seismology).

5. New Software and Platforms

5.1. COFFEE

FUNCTIONAL DESCRIPTION

COFFEE is a 3D solver for linear elastodynamics based on fast BEMs (full implementation in Fortran 90). The 3-D elastodynamic equations are solved with the boundary element method accelerated by the multi-level fast multipole method or H-matrix based solvers. The fundamental solutions for the infinite or half-space are used. A boundary element-boundary element coupling strategy is also implemented so multi-region problems (strata inside a valley for example) can be solved.

- Contact: Stéphanie Chaillat
- URL: http://perso.ensta-paristech.fr/ chaillat/index.php?page=softwares

5.2. XLiFE++

FUNCTIONAL DESCRIPTION

XLiFE++ is a Finite Element library written in C++ based on a variational approach and standard finite element methods, boundary element methods, spectral approximations. It allows to mix these different methods in a easy way to deal with complex models. A new version (v1.3) has been released in December 2015 but it is still in progress. This year, the main new features are: finite elements at any order (before, they were available up to order 6), some edge elements at any order (Raviart-Thomas, Nedelec), more stable boundary element methods. The performance was highly improved and first tests with multithreading (using OpenMP) have been done. At last, a lot of work to improve and stabilize user interface was done about mesh integrated tools, solvers, and external libraries installation. To make further progress in BEM methods (FMM, H Matrix, SCSD), a DGA project started in October 2015 in collaboration with MyBEM software team at CMAP (François Allouges, Matthieu Aussal, ...). Nicolas Salles has been recruited to enhance the BEM part of XLiFE++.

- Contact: Eric Lunéville
- URL: http://uma.ensta-paristech.fr/soft/XLiFE++/

6. New Results

6.1. Wave propagation in non classical media

6.1.1. Modal analysis of electromagnetic dispersive media

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

Except in vacuum, the velocity of electromagnetic waves generally depends on the frequency. This dispersion plays in particular a vital role in situations where the effective index takes values below unity or negative, which happens with metamaterials or plasmonic devices. However, most of the studies in this domain are considering only the time-harmonic regime, forgetting dispersion, which leads to apparent paradoxes. We have elaborated a project, in collaboration with the Institut Fresnel in Marseille. Our objective is to gather physical and mathematical points of view to explore a frequency-to-time approach for dispersive media. This approach is based on a general technique which allows to hide dispersion in an augmented formulation of Maxwell's equations. Using this tool, our aim is first to carry the spectral analysis of dispersive systems, take advantage of this analysis to predict the time-dependent behaviour of dispersive systems, then design adapted numerical methods for their simulation and finally confirm predictions by real experiments. To begin with, during the internship of Bilal Yezza, a toy problem has been studied, where the presence of accumulation points in the spectrum is due to the dispersion. This project has been submitted to the ANR for the second year and has already led to preliminary common works and discussions, in particular during the workshop *Leaky days* organized by Christophe Hazard in Palaiseau in June 2015.

6.1.2. Perfectly Matched Layers in plasmas and metamaterials

Participants: Eliane Bécache, Patrick Joly, Maryna Kachanovska, Valentin Vinoles.

We work on the stability of Generalized Perfectly Matched Layers (GPMLs) in dispersive media for which classical PMLs are in general unstable. These new PMLs involve, in addition to the absorption parameter $\sigma \geq 0$, a real valued rational function of the frequency $\psi(\omega)$. We first worked on isotropic media and derived, using Fourier analysis methods, a necessary and sufficient condition on the function $\psi(\omega)$ for the stability of the PML model. This result has been presented in several conferences and used to design new stable PMLs for negative index metamaterials and uniaxial anisotropic plasmas (even though this last model is anisotropic, the anisotropy has a structure that permits a special decomposition of vector fields that give a new equivalent model adapted for our GPMLs).

We are currently working on the generalization of this analysis to a class of anisotropic dispersive models using a different approach based on Laplace transform in time.

However, this theory does not apply to more general cold plasma models that we wish to treat. Finding good PMLs in this case still remains a challenging open question. Several attempts, such as radial PMLs (which we discussed about with our visitor Martin Halla from TU Wien), have failed.

6.2. Wave propagation in heterogeneous media

6.2.1. Homogenization of layered media

Participant: Jean-François Mercier.

Metamaterials have revived interest in the theory of homogenization techniques because some standard techniques, based on the Ross Nicholson-Weir method, can lead to unphysical effective parameters, since depending on the incident wave. In collaboration with Agnès Maurel and Abdelkader Ourir from the Langevin Institut and Simon Felix from the LAUM, we have proposed more suitable homogenization methods to describe wave propagation in artificial environments, by considering homogenization of sliced media. When the medium is structured at a sub-wavelength scale, it can be described as a simpler equivalent medium, homogeneous and anisotropic, with a tensor mass density and an effective modulus of elasticity. We considered two cases:

- for a propagating incident wave, we obtained the diffusion properties of the medium and we have shown that the effective medium correctly captures the acoustic properties of the real medium.

- however, in the real problem, evanescent waves are generated and if one of them is resonant, the properties of transmission and reflection of the incident wave are changed: this happens for the electromagnetic waves (Wood anomalies, "spoof plasmon"). To capture these resonance effects, we have considered evanescent incident waves. We then showed that the homogenization predicts the dispersion curves of the resonant waves: in the homogenized problem, they correspond to guided waves by the anisotropic layer.

6.2.2. High order transmission conditions between homogeneous and homogenized periodic half-spaces

Participants: Sonia Fliss, Valentin Vinoles.

This work is a part of the PhD of Valentin Vinoles, and is done in collaboration with Xavier Claeys (LJLL, Paris VI). It is motivated by the fact that classical homogenization theory poorly takes into account interfaces, which is particularly unfortunate when considering negative materials, because important phenomena arise precisely at their surface (plasmonic waves for instance). To overcome this limitation, we want to construct high order transmission conditions. Using matched asymptotics, we have treated the case of a plane interface between a homogeneous and a homogenized periodic half space. The analysis is based on an original combination of Floquet-Bloch transform and a periodic version of Kondratiev techniques. The obtained conditions involve Laplace- Beltrami operators at the interface and require to solve *cell problems* in infinite strips. The numerical computations are based on specific transparent conditions for periodic media. The error analysis and the numerical study are on-going works.

6.2.3. Scattering by small heterogeneities

Participants: Patrick Joly, Simon Marmorat.

Simon Marmorat has defended his thesis, done in collaboration with the CEA-LIST and with Xavier Claeys (LJLL, Paris VI). The goal was to develop an efficient numerical approach to simulate the propagation of waves in concrete, which is modelled as a smooth background medium, with many small embedded heterogeneities. To do so, one has proposed two reduced models relying on the asymptotic analysis of the problem with respect to the (small) size of the heterogeneities. The first model looks like a fictitious domain method in which the analysis of the near field (closed to the heterogeneities) is exploited. The second one is a method of auxiliary sources, based on the analysis of the far field (far from the heterogeneities). Rigorous error estimates have been established. From the numerical point of view, some points, related to the Galerkin enrichment of standard finite element methods, still need to be completed.

6.2.4. Effective boundary conditions for strongly heterogeneous thin layers

Participants: Mathieu Chamaillard, Patrick Joly.

This topic is the object of the PhD of Mathieu Chamaillard, done in collaboration with Houssem Haddar (Inria, Defi). We are interested in the construction of effective boundary conditions for the diffraction of waves by an obstacle covered with a thin coating whose physical characteristics vary “periodically”. The width of the coating and the period are both proportional to the same small parameter δ.

The results obtained previously on scalar propagation models have been extended to 3D Maxwell’s equations resulting in the construction of an effective condition of the form $E \times n = \delta ik \mathcal{Z}_\Gamma \left(n \times (H \times n)\right)$ where the impedance operator $\mathcal{Z}_\Gamma$, a second order tangential differential operator along Γ, depends on the geometry of the obstacle and of the material properties of the coating. The analysis, which is much more involved than in the scalar case (in particular in what concerns the stability analysis), provides error estimates in $O(\delta^2)$.

The thesis will be defended in the end of January 2016.

6.3. Spectral theory and modal approaches for waveguides

6.3.1. Guided modes in ladder-like open periodic waveguides

Participants: Sonia Fliss, Patrick Joly, Khac Long Nguyen, Elizaveta Vasilevskaya.

The general objective is the study of localized modes in locally perturbed periodic media and of guided modes in periodic media with a lineic perturbation. We investigate the existence theory of such modes as well as their numerical computations.

The problem, that is investigated in the framework of the PhD thesis of E. Vasilevskaya, in collaboration with Bérangère Delourme (Paris 13 University), is the case where the propagation medium is a thin structure whose limit is a periodic graph. We exhibit situations where the introduction of a line defect into the geometry of the domain leads to the appearance of guided modes. From the theoretical point of view, the problem is studied by asymptotic analysis methods, the small parameter being the thickness of the domain, so that when the thickness of the structure is small enough, the domain approaches a graph. The spectral theory of the underlying limit operator defined in the graph plays a key role in the analysis. For 2D configurations, we have shown that for sufficiently thin structures, it suffices to reduce the width of one rung to make appear guided modes. Moreover, using matched asymptotic expansions, we have constructed asymptotic expansions at any order of the corresponding eigenvalues and guided modes. For 3D configurations, the spectral theory of the underlying limit operator was already studied. In a further step, one can expect, again by asymptotic analysis, to get corresponding existence results for the original problem, at least for sufficiently thin structures.

From a numerical point of view, the modes can be computed using non linear eigenvalue problems and specific transparent boundary conditions for periodic media. During his post-doc, Khac Long Nguyen has implemented an exact method based on Dirichlet-to-Neumann operators to compute localized modes in 2D locally perturbed periodic media or guided modes in 3D periodic media with a lineic perturbation. This was already done few years ago for waveguides configurations but here the construction of the transparent boundary conditions are much more involved.

6.3.2. Reduced graph models for networks of thin co-axial electromagnetic cables

Participants: Geoffrey Beck, Patrick Joly.

This work is the object of the PhD of Geoffrey Beck and is done in collaboration with Sébastien Imperiale (Inria, MEDISIM). The general context is the non destructive testing by reflectometry of electric networks of co-axial cables with heterogeneous cross section and lossy materials, which was the subject of the ANR project SODDA. We consider electromagnetic wave propagation in a network of thin coaxial cables (made of a dielectric material which surrounds a metallic inner-wire). The goal is to reduce 3D Maxwell's equations to a 1D like model. During the past two years, we derived and justified generalized telegraphers model for a single cable. This year, we incorporated in our model the losses due to the skin effect induced by the non perfectly conducting nature of the metallic wire. Finally using the method of matched asymptotics, we have derived and justified improved Kirchhoff conditions.

6.3.3. Multimodal methods for the propagation of acoustic and electromagnetic waves

Participant: Jean-François Mercier.

In collaboration with Agnès Maurel from the Langevin Institut and Simon Felix from the LAUM, we have developed fast multimodal methods to describe the acoustic propagation in rigid waveguides or in periodic arrays. An incident wave is scattered by penetrable inclusions or by the succession of different penetrable media separated by interfaces of any shape. The difficulties are: to take into account the modes coupling and to get modes naturally decoupled at the entrance and at the exit of the computational domain. A weak formulation of the problem provides a modal formulation taking exactly into account the matching conditions at the interfaces. A consequence is that the obtained convergence is the best convergence expected, given the regularity of the solution. After the study of isotropic cases, we have generalized this approach to the case of anisotropic media, the difficulty being to take into account a tensor in the propagation equation.

6.3.4. Plasmonic waveguides

Participants: Anne-Sophie Bonnet-Ben Dhia, Camille Carvalho, Patrick Ciarlet.

This work, which is a part of the PhD of Camille Carvalho, is done in collaboration with Lucas Chesnel (Inria, Defi). A plasmonic waveguide is a cylindrical structure consisting of metal and dielectric parts. In a certain frequency range, the metal can be seen as a lossless material with a negative dielectric permittivity. The study of the modes of a plasmonic waveguide is then presented as an eigenvalue problem with a sign-change of coefficients in the main part of the operator. Depending on the values of the contrast of permittivities at the metal / dielectric interface, different situations may occur. In the "good" case, the problem is self-adjoint with compact resolvent and admits two sequences of eigenvalues tending to + and -∞. But when the interface presents corners, for a particular contrast range, the problem is neither self-adjoint nor with compact resolvent. In this case, Kondratiev's theory of singularities allows to build extensions of the operator, with compact resolvent. Finally, we show that the eigenvalues for one of these extensions can be computed by combining finite elements and Perfectly Matched Layers at the corners. The paradox is that a specific treatment has to be done to capture the corners singularities, even to compute regular eigenmodes.

6.4. Inverse problems

6.4.1. Quasi-Reversibility method and exterior approach for evolution problems

Participant: Laurent Bourgeois.

This work is a collaboration with Jérémi Dardé from Toulouse University. We address some linear ill-posed problems involving the heat or the wave equation, in particular the heat/wave equation with lateral Cauchy data. We have introduced several kinds of variational mixed formulations of quasi-reversibility which enable us to solve these ill-posed problems by using classical Lagrange finite elements. We have also designed a new approach called the "exterior approach" to solve inverse obstacle problems with initial condition and lateral Cauchy data for the heat/wave equation. It is based on a combination of an elementary level set method and the quasi-reversibility methods we have just mentioned. Some numerical experiments have proved the feasibility of our strategy to identify obstacles from lateral Cauchy data for the heat equation in 2D and for the wave equation in 1D. Our objective is now to focus on the wave equation in 2D. Firstly we wish to obtain a minimal value of the final time in order to ensure uniqueness of the obstacle from the lateral Cauchy data. Secondly we want to test our exterior approach numerically. We expect better results than with the heat equation.

6.4.2. Higher-order expansion of misfit functional for defect identification in elastic solids

Participants: Marc Bonnet, Rémi Cornaggia.

This work, done in the context of the PhD of Rémi Cornaggia, concerns the identification of scatterers of moderate size, modelled as elastic inhomogeneities embedded in an homogeneous elastic background medium, by time-harmonic elastodynamic measurements. Least-squares functionals, commonly used for defect identification, are expanded in powers of the small characteristic radius a of a trial inhomogeneity. This entails the expansion of the elastodynamic scattering problem, which is needed only on the support of the trial inhomogeneity and is established by means of a Lippmann-Schwinger volume integral equation. This approach generalizes, to higher orders in a, the well-known concept of topological derivative. Such expansion, whose derivation and evaluation are facilitated by using an adjoint state, provides a basis for the quantitative estimation of flaws whereby a region of interest may be exhaustively probed at reasonable computational cost. So far, the higher-order expansion has been derived under fairly general conditions, mathematically justified, and demonstrated on simple numerical examples involving the identification of a spherical inhomogeneity in an unbounded 3D medium.

6.4.3. Complete transmission invisibility in waveguides

Participant: Anne-Sophie Bonnet-Ben Dhia.

In collaboration with Lucas Chesnel (Inria, Defi) and Sergei Nazarov (Saint-Petersburg University), we consider time harmonic acoustic problems in waveguides. We are interested in finding localized perturbations of a straight waveguide which are not detectable in the far field, as they produce neither reflection nor conversion of propagative modes. In other words, such *invisible* perturbation produces a scattered field which is exponentially decaying at infinity in the two infinite outlets of the waveguide.

In our previous contributions, we found a way to build smooth and small perturbations of the boundary which were almost invisible, in the sense that they were producing no reflexions but maybe a phase shift in transmission.

During the visit of Sergei Nazarov, we found a new approach which allows to build completely invisible perturbations in the mono-mode regime (i.e. when the frequency is chosen below the first cut-off frequency) with no phase shift in transmission. These perturbations include some kinds of thin resonators whose height is adapted to the frequency.

All our results mainly rely on asymptotic theory.

6.4.4. Energy-based cost functional for three-dimensional transient elastodynamic imaging

Participant: Marc Bonnet.

This work is a continuing collaboration with Wilkins Aquino (Duke University, USA). It is concerned with three-dimensional elastodynamic imaging by means of the modified error in constitutive relation (MECR), combining the energy norm of the constitutive residual and a more-classical L^2 norm on the measurement residuals.

We have in particular considered the case of imaging using interior data. The stationarity equations associated with the minimization of a MECR objective function, subject to the conservation of linear momentum, yields a well-posed problem coupling two elastodynamic fields, even in cases where boundary conditions are initially underspecified (making it difficult to define *a priori* a forward problem). Numerical results demonstrate the robust performance of the method in situations where the available measurement data is incomplete and corrupted by noise of varying levels.

In a separate study, elastodynamic imaging using transient data and based on time-domain solvers has been investigated. In this context, each evaluation of a time-domain MECR cost functional entails solving two elastodynamic problems (one forward, one backward), which moreover are coupled (unlike the case of L^2 misfit functionals). This coupling creates a major computational bottleneck, making MECR-based inversion difficult for spatially 2D or 3D configurations. To overcome this obstacle, we propose to (a) set the entire computational procedure in a consistent time-discrete framework that incorporates the chosen time-stepping algorithm, and (b) use an iterative successive over-relaxation-like method for the resulting stationarity equations. The resulting MECR-based inversion algorithm is formulated under quite general conditions, allowing for 3D transient elastodynamics, straightforward use of available parallel solvers, a wide array of time-stepping algorithms commonly used for transient structural dynamics, and flexible boundary conditions and measurement settings. The proposed MECR algorithm is then demonstrated on computational experiments involving 2D and 3D transient elastodynamics and up to over 500 000 unknown elastic moduli.

6.4.5. Linear Sampling Method with realistic data in waveguides

Participants: Laurent Bourgeois, Arnaud Recoquillay.

Our activities in the field of inverse scattering in waveguides with the help of sampling methods has now a quite long history. We now intend to apply these methods in the case of realistic data, that is surface data in the time domain. This is the subject of the PhD of Arnaud Recoquillay. It is motivated by Non Destructive Testing activities for tubular structures and is the object of a partnership with CEA List (Vahan Baronian).

Our strategy consists in transforming the time domain problem into a multi-frequency problem by the Fourier transform. This allows us to take full advantage of the established efficiency of modal frequency-domain sampling methods. We have already proved the feasibility of our approach in the 2D acoustic case. In particular, we have shown how to optimize the number of sources/receivers and the distance between them in order to obtain the best possible identification result. The next steps consist in extending such an approach to the elastic case and trying it experimentally, that is with real data. Experiments will be carried in CEA.

6.5. Integral equations

6.5.1. Fast BEM solvers based on $\mathcal{H}$-matrices for 3-D frequency-domain elastodynamics

Participants: Stéphanie Chaillat, Patrick Ciarlet, Luca Desiderio.

The main advantage of the Boundary Element Method (BEM) is that only the domain boundaries are discretized leading to a drastic reduction of the total number of degrees of freedom. In traditional BE implementation the dimensional advantage with respect to domain discretization methods is offset by the fully-populated nature of the BEM coefficient matrix. Using the $\mathcal{H}$-matrix arithmetic and low-rank approximations (performed with Adaptive Cross Approximation) it is possible to derive fast iterative and direct solvers for the BEM system. We extend the method to 3-D frequency-domain elastodynamics. To this end, the Adaptive Cross Approximation is adapted to deal with vectorial problems. To validate the accuracy of the solution of the LU based direct solver, we derive an error estimate. Finally, we check numerically the theoretical estimate of the storage costs. In particular, we study the efficiency of low-rank approximations when the frequency is increased. This is done in partnership with SHELL company in the framework of the PhD of Luca Desiderio.

6.5.2. OSRC preconditioner for 3D elastodynamics

Participant: Stéphanie Chaillat.

This work is done in collaboration with Marion Darbas from University of Picardie and Frédérique Le Louer from Technological University of Compiègne. The fast multipole accelerated boundary element method (FM-BEM) is a possible approach to deal with scattering problems of time-harmonic elastic waves by a three-dimensional rigid obstacle. In 3D elastodynamics, the FM-BEM has been shown to be efficient with solution times of order $O(N \log N)$ per iteration (where N is the number of BE degrees of freedom). However, the number of iterations in GMRES can significantly hinder the overall efficiency of the FM-BEM. To reduce the number of iterations, we propose a clever integral representation of the scattered field which naturally incorporates a regularizing operator. When considering Dirichlet boundary value problems, the regularizing operator is a high-frequency approximation to the Dirichlet-to-Neumann operator. For a spherical obstacle, the approximation of the DtN is a linear combination of the tangential and normal parts. The numerical efficiency of the preconditioned integral equation (i.e. the independence of the number of iterations from the mesh size and frequency) is verified for spherical obstacles, validating the concept of analytical preconditioners for 3D elastodynamics FM-BEM. For more general shapes, this approximation of the DtN is more complex to derive. As a first step, we construct and validate the approximation in the framework of the On-Surface Radiation Condition (OSRC) method.

6.5.3. A wideband Fast Multipole Method for oscillatory kernels

Participant: Stéphanie Chaillat.

This work is done in collaboration with Francis Collino. We derive a new Fast Multipole Method (FMM) based on plane wave expansions (PWFMM), combining the advantages of the low and high frequency formulations. We revisit the method of Greengard et al. (1998) devoted to the low frequency regime and based on the splitting of the Green's function into a propagative and an evanescent part. More precisely, we give an explicit formula of the filtered translation function for the propagative part, we derive a new formula for the evanescent part and we provide a new interpolation algorithm. At all steps, we check the accuracy of the method by providing error estimates. These theoretical developments are used to propose a wideband FMM based entirely on plane wave expansions. The numerical efficiency and accuracy of this broadband PWFMM are illustrated with a numerical example.

6.5.4. Coupling integral equations and high-frequency methods for ultrasonic NDT modelling

Participants: Marc Bonnet, Laure Pesudo.

This work, in partnership with CEA LIST and in collaboration with Francis Collino, is undertaken in the context of the PhD thesis of Laure Pesudo. Modelling ultrasonic non destructive testing (NDT) experiments simultaneously involves the scattering of waves by defects of moderate size (for which discretization-based methods such as the BEM are appropriate) and propagation over large distances (requiring high-frequency approximations). Those two types of simulation methods are therefore simultaneously needed in NDT modelling but do not lend themselves easily to coupling. The coupling approach proposed here takes advantage of the fact that the far-field asymptotic approximation of integral representation formulas (which accurately account for the scattering by defects) yields a superposition of rays (satisfying the leading-order equations arising from high-frequency asymptotics). This allows to convert incoming rays into plane waves, compute their scattering by obstacles, and convert the scattered field into rays. A defect of given shape and characteristics becomes (approximately) represented as a point-like scatterer with anisotropic reflection properties that are computed (offline) from BEM solutions of near-field problems. Using a partition of unity on the obstacle boundary allows to approximate the obstacle by a set of point-like reflectors, thereby enlarging the size of obstacles amenable to this approach. Preliminary tests on 2D scalar wave propagation problems show that sufficient far-field accuracy is achieved for wavelength-sized defects.

6.5.5. Dynamic soil-structure interaction

Participants: Marc Bonnet, Stéphanie Chaillat, Zouhair Adnani.

This work, undertaken in the context of the PhD thesis of Zouhair Adnani (CIFRE partnership with EDF), concerns the simulation of dynamic soil-structure interaction (SSI) in connection with seismic assessment of civil engineering structures. The main goal is to formulate, implement, and evaluate on realistic test examples, a computational strategy that combines the fast multipole integral equation method for elastic wave propagation in unbounded regions (COFFEE FMM-accelerated BEM solver), and finite elements for modelling civil engineering structures and neighboring soil regions (the EDF in-house code Code_Aster). In a preliminary phase, the evaluation of transient elastodynamic responses via the Fourier synthesis of frequency-domain solutions computed using COFFEE (see Section 5.1) has been studied on several test problems, achieving substantial improvements of computational efficiency for this component of SSI analysis.

6.5.6. Volume Integral Formulations

Participant: Marc Bonnet.

Volume integral equations (VIEs), also known as Lippmann-Schwinger integral equations, arise naturally when considering the scattering of waves by penetrable, and possibly heterogeneous, inhomogeneities embedded in a homogeneous background medium. In contrast with the vast existing literature on boundary integral equations, comparatively few studies are available regarding the mathematical properties of VIEs. In this work, we investigate the solvability of VIE formulations arising in elastodynamic scattering by penetrable obstacles. The elasticity tensor and mass density are allowed to be smoothly heterogeneous inside the obstacle and may be discontinuous across the background-obstacle interface, the background elastic material being homogeneous. Both materials may be anisotropic, within certain limitations for the background medium. The VIE associated with this problem is derived, relying on known properties of the background fundamental tensor. To avoid difficulties associated with existing radiation conditions for anisotropic elastic media, we propose an alternative definition of the radiating character of transmission solutions. The unique solvability of the volume integral equation (and of the scattering problem) is established. For the important special case of isotropic background properties, our definition of a radiating solution becomes equivalent to the classical Sommerfeld-Kupradze radiation conditions.

6.6. Domain decomposition methods

6.6.1. Transparent boundary conditions with overlap in unbounded anisotropic media

Participants: Anne-Sophie Bonnet-Ben Dhia, Sonia Fliss, Antoine Tonnoir.

We are interested in acoustic or elastic wave propagation in time harmonic regime in a 2D or 3D medium which is a local perturbation of an infinite anisotropic homogeneous medium. We investigate the question of deriving a formulation which is suitable for numerical computations. This question is difficult due to the anisotropy of the surrounding medium. Our approach consists in coupling several plane-waves representations of the solution in half-spaces surrounding the defect with a FE computation of the solution around the defect. The difficulty is to ensure that all these representations match, in particular in the infinite intersections of the half-spaces. It leads to a formulation which couples, via integral operators, the solution in a bounded domain including the defect and its traces on the edge of the half-planes. We have shown that this formulation has good properties from theoretical and numerical points of view.

6.6.2. Electromagnetic scattering by objects with multi-layered dielectric coatings

Participants: Patrick Joly, Matthieu Lecouvez.

The PhD thesis of Matthieu Lecouvez, undertaken in collaboration with the CEA-CESTA and Francis Collino, has been defended in July. It concerned the diffraction of time harmonic electromagnetic waves by perfectly conducting objects covered by multi-layered (possibly thin) dielectric coatings. This idea was to use a domain decomposition method in which each layer would constitute a subdomain. The transmission conditions between the subdomains involve some specific impedance operators in order to achieve a geometric convergence of the method (compared to the slow algebraic convergence obtained with standard Robin conditions). This year, the theoretical aspects of our work have been completed and are the object of an article in preparation.

6.6.3. Domain Decomposition Methods for the neutron diffusion equation

Participants: Patrick Ciarlet, Léandre Giret.

Studying numerically the steady state of a nuclear core reactor is expensive, in terms of memory storage and computational time. In its simplest form, one must solve a neutron diffusion equation with low-regularity solutions, discretized by finite element techniques, totaling millions of unknowns or more, within a loop. Iterating in this loop allows to compute the smallest eigenvalue of the system, which determines the critical, or non-critical, state of the 3D core configuration. This problem fits within the framework of high performance computing so, in order both to optimize the memory storage and to reduce the computational time, one can use a domain decomposition method, which is then implemented on a parallel computer. The definition of an efficent DD method has been addressed for conforming meshes prior to the PhD research of Léandre Giret. The development of non-conforming, hence more flexible, DD methods has recently been finalized.
The optimization of the eigenvalue loop is under way. The current research also focuses on the numerical analysis of the full suite of algorithms to prove convergence for the complete multigroup SPN model (which involves coupled diffusion equations). Realistic computations will be carried out with the APOLLO3 neutronics code.
This topic is developed in partnership with CEA-DEN (Erell Jamelot).

6.7. Aeroacoustics

6.7.1. Time-harmonic acoustic scattering in a vortical flow

Participants: Antoine Bensalah, Patrick Joly, Jean-François Mercier.

This activity is done in the framework of the PhD of Antoine Bensalah, in partnership with Airbus Group. We study the time-harmonic acoustic radiation in a fluid in a general flow which is not curl free, but has restricted vortical areas. The objective is to take into account the complicated coupling between acoustics and hydrodynamics. The Galbrun approach developed previously in 2D is too expensive in terms of degrees of freedom for 3D simulations. As an alternative, we propose to consider instead the Goldstein equations, which are vectorial only in the vortical areas and remain scalar elsewhere.

We have proved that the Goldstein equations are well-posed in a domain Ω for a potential flow, or for a vortical flow if the flow is Ω-filling (each point of Ω is reached by a streamline coming from the inflow boundary in a finite time). A non Ω-filling flow corresponds to the presence or recirculations areas and we have shown that, for such flows, some of the closed streamlines can be resonant. To study deeper this phenomenon, we focused on the case of a rotating flow in an annular geometry. We proved that outside the set of resonance frequencies, the radiation problem is well-posed. Work is under progress to determine the solution on a resonant streamline.

6.7.2. Propagation of solitons through Helmholtz resonators

Participant: Jean-François Mercier.

With Bruno Lombard (Laboratoire de Mécanique et Acoustique of Marseille), we studied the propagation of an acoustic solitary wave in a 1D waveguide connected to a periodic array of Helmholtz resonators. Starting from a model of the literature, obtained by approximations, our goal was to provide a numerical modeling, which validates (or not) the underlying model and the assumptions. The model consists of two coupled equations evolution: a nonlinear PDE describing acoustic waves (similar to the Burgers equation), and a linear ODE describing oscillations in the Helmholtz resonators. We have developed a numerical method based on two main ingredients: a diffusive representation of fractional derivatives and a splitting method applied to the evolution equations. The numerical scheme has been validated by comparison with exact solutions. The properties of non-linear solutions have been investigated numerically.

In collaboration with O. Richoux of the LAUM, this work has been extended, comparing to experimental results. Adjustments had to be made, the attenuation of the numerical model being weaker than that observed experimentally. To remedy this, we have incorporated some attenuation mechanisms that we had neglected. One consequence of these additions is that a more sophisticated numerical method had to be developed. A good agreement has been found with experimental results.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

Contract POEMS-DGA
Participants: Anne-Sophie Bonnet-Ben Dhia, Sonia Fliss, Patrick Joly.

Start : 09/01/2011, End : 12/31/2015. Administrator : ENSTA.
This contract is about guided waves in photonic crystals : we want to develop new mathematical and numerical tools for the characterization, the study and the computation of the guided modes in photonic crystals.

Contract POEMS-DGA
Participants: Eric Lunéville, Marc Lenoir, Séphanie Chaillat, Nicolas Kielbasiewicz, Nicolas Salles.

Start : 2015, End : 2018. Administrator : ENSTA.
This contract is in partnership with François Alouges and Matthieu Aussal (CMAP, Ecole Polytechnique) and concerns the improvement of Boundary Element Methods for wave propagation problems.

Contract POEMS-CEA-LIST
Participants: Marc Bonnet, Laure Pesudo.

Start : 12/01/2014, End : 11/31/2017. Administrator : CNRS.
This contract is about the coupling between high frequency methods and integral equations.

Contract POEMS-SHELL
Participants: Stéphanie Chaillat, Patrick Ciarlet, Luca Desiderio.

Start : 10/01/2013, End : 09/31/2016. Administrator : CNRS.
This contract is about fast direct solvers to simulate seismic wave propagation in complex media.

Contract POEMS-EDF
Participants: Stéphanie Chaillat, Marc Bonnet, Zouhair Adnani.

Start : 12/01/2014, End : 11/31/2017. Administrator : CNRS.
This contract is about fast solvers to simulate soil-structure interactions.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- ANR project *METAMATH: modélisation mathématique et numérique pour la propagation des ondes en présence de métamatériaux.* Partners: EPI DEFI (Inria Saclay), IMATH-Université de Toulon, LJLL-Paris 6 University.
  Start : 12/01/2011, End : 11/30/2016. Administrator : Inria. Coordinator : Sonia Fliss.
- ANR project *CHROME: Chauffage , réflectométrie et Ondes pour les plasmas magnétiques*
  Partners: LJLL-Paris 6 University, Université de Lorraine
  Start : 10/01/2012, End : 10/01/2015 Administrator : Inria Coordinator for POEMS: Eliane Bécache
- ANR project *RAFFINE: Robustesse, Automatisation et Fiabilité des Formulations INtégrales en propagation d'ondes : Estimateurs a posteriori et adaptivité*
  Partners: EADS, IMACS, ONERA, Thales
  Start : January 2013. End : december 2016. Administrator : Inria. Coordinator: Marc Bonnet.
- ANR project *ARAMIS: Analyse de méthodes asymptotiques robustes pour la simulation numérique en mécaniques*
  Partners: Université de Pau, Université technologique de Compiègne
  Start : January 2013. End : December 2016. Administrator : Université de Pau. Participant for POEMS: Marc Bonnet
- ANR project *Non-Local Domain Decomposition Methods in Electromagnetism.*
  Partners: Inria Alpines, Inria POEMS, Inria Magique 3D.
  Start : 2015, End : 2019. Administrator : Inria. Coordinator: Xavier Claeys.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. BATWOMAN

Type: FP7 Marie Curie

Objectif: Basic Acoustics Training - & Workprogram On Methodologies for Acoustics - Network

Duration: September 2013 - August 2017

Coordinator: Martin Wifling, VIRTUAL VEHICLE (AT)

Inria contact: P. Joly

Abstract: The BATWOMAN ITN aims at structuring research training in basic and advanced acoustics and setting up a work program on methodologies for acoustics for skills development in a highly diverse research field offering multiple career options.

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. Informal International Partners

Wilkins Aquino (Duke University)

Eric Chung (Chinese University of Hong Kong)

Bojan Guzina (University of Minnesota)

Sergei Nazarov (Saint-Petersburg University)

Jeronimo Rodriguez (University of Santiago de Compostela)

8.3.2. Participation In other International Programs

Groupement De Recherche Européen : GDRE-US

This European Research Network (GDRE) entitled *Wave Propagation in Complex Media for Quantitative and Non Destructive Evaluation* aims at giving opportunities for interactions between researchers on the occasion of informal meetings, workshops and colloquia, alternatively in France and in the UK. It linked groups of academics and researchers in Ultrasonic Wave Phenomena with each other, and with industrial research centres and companies. The teams involved focused particularly on the theoretical end of the research spectrum, and include mathematicians, physicists and engineers.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Advisory and management activities

- P. Joly is a member of the scientific committee of CEA-DAM.
- E. Lunéville is the Head of UMA (Unité de Mathématiques Appliquées) at ENSTA ParisTech.

9.1.2. Scientific events organisation end selection

- E. Bécache, A. S. Bonnet-Ben Dhia, M. Bonnet, C. Hazard, P. Joly and E. Lunéville have been members of the scientific committee for the 12th international conference on mathematical and numerical aspects of wave propagation, which has been held in Karlsruhe in July 2015.
- A. S. Bonnet-Ben Dhia has been a member of the organizing committee of the workshop *Waveguides: asymptotic methods and numerical analysis* which has been held in Napoli in May 2015.
- P. Joly has been a member of the organizing committee of the workshop *Asymptotic analysis and spectral theory* which has been held in Orsay in October 2015.

9.1.3. Journal

- A. S. Bonnet-Ben Dhia is associate editor of SINUM (SIAM Journal of Numerical Analysis).
- M. Bonnet is associate editor of Engineering Analysis with Boundary Elements
- M. Bonnet is in the editorial board of Inverse Problems.
- M. Bonnet is in the editorial board of Computational Mechanics.
- M. Bonnet is in the editorial board of Journal of Optimization Theory and Application.
- P. Ciarlet is an editor of CAMWA (Computers & Mathematics with Applications).
- P. Ciarlet is an editor of ESAIM:M2AN (Mathematical Modeling and Numerical Analysis).
- P. Joly is an editor of ESAIM:M2AN (Mathematical Modeling and Numerical Analysis).
- P. Joly is a member of the editorial board of AAMM (Advances in Applied Mathematics and Mechanics).
- P. Joly is a member of the Book Series Scientific Computing of Springer Verlag.
- The team members regularly review papers for many international journals.

9.2. Teaching - Supervision

9.2.1. Teaching

Eliane Bécache

- *Méthode des éléments finis*, ENSTA ParisTech (2nd year)

- *Compléments sur la méthode des éléments finis*, ENSTA ParisTech, (2nd year)
- *Fonctions d'une variable complexe*, ENSTA ParisTech (1st year)

Marc Bonnet

- *Problèmes inverses*, Master MS2SC (Centrale Paris and ENS Cachan)
- *Méthodes intégrales*, Master TACS (ENS Cachan)
- *Outils élémentaires d'analyse pour les équations aux dérivées partielles*, ENSTA ParisTech (1st year)

Anne-Sophie Bonnet-Ben Dhia

- *Fonctions d'une variable complexe*, ENSTA ParisTech (1st year)
- *Propagation dans les guides d'ondes*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)
- *Etude mathématique de quelques problèmes de transmission avec coefficients changeant de signe*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)
- *Théorie spectrale des opérateurs autoadjoints et applications aux guides optiques*, ENSTA ParisTech (2nd year)

Laurent Bourgeois

- *Outils élémentaires pour l'analyse des équations aux dérivées partielles*, ENSTA ParisTech (1st year)
- *Inverse problems: mathematical analysis and numerical algorithms*, (Master AN& EDP, Paris 6 and Ecole Polytechnique)
- Speaker in the Franco-German Summer School Inverse Problems for Waves, Ecole Polytechnique, August 24-28, 2015.

Stéphanie Chaillat

- *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA ParisTech (1st year)
- *Fonctions d'une variable complexe*, ENSTA ParisTech (1st year)
- *Equations intégrales et multipôles rapides*, Ecole doctorale MODES (Univ. Paris Est, Marne la Vallée)
- *Résolution des problèmes de diffraction par équations intégrales*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)

Colin Chambeyron

- *Analyse réelle: optimisation libre et sous contraintes*, Dauphine University (1st year)
- *Outils mathématiques*, Dauphine University (1st year)
- *Algèbre linéaire*, Dauphine University (2nd year)

Patrick Ciarlet

- *Compléments sur la méthode des éléments finis*, ENSTA ParisTech (2nd year)
- *Theory and algorithms for distributed computing*, ENSTA ParisTech (3rd year), and Master "Modeling and Simulation" (M2)
- *Maxwell's equations and their discretization*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)
- *Etude mathématique de quelques problèmes de transmission avec coefficients changeant de signe*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)

Sonia Fliss

- *Méthode des éléments finis*, ENSTA ParisTech (2nd year)

- *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA ParisTech (1st year).
- *Propagation des ondes dans les milieux périodiques*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)
- *Homogeneisation*, Master ANEDP Paris 6 and Ecole Polytechnique (M2)

Christophe Hazard

- *Outils élémentaires d'analyse pour les équations aux dérivées partielles*, ENSTA ParisTech (1st year)
- *Théorie spectrale des opérateurs autoadjoints et applications aux guides optiques*, ENSTA ParisTech (2nd year)

Patrick Joly

- *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA ParisTech (1st year)
- *Outils élémentaires d'analyse pour les équations aux dérivées partielles*, ENSTA ParisTech (1st year)
- *Propagation des ondes dans les milieux périodiques*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)
- Speaker in the Franco-German Summer School Inverse Problems for Waves, Ecole Polytechnique, August 24-28, 2015.

Nicolas Kielbasiewicz

- *Programmation scientifique et simulation numérique*, ENSTA ParisTech (2nd year)
- *Parallélisme et calcul réparti*, ENSTA ParisTech (Master 2)

Marc Lenoir

- *Fonctions d'une variable complexe*, ENSTA ParisTech (2nd year)
- *Equations intégrales*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)
- *Méthodes asymptotiques hautes fréquences pour les équations d'ondes - course notes*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)

Eric Lunéville

- *Introduction au Calcul Scientifique*, ENSTA ParisTech (2nd year).
- *SIMNUM : Simulation numérique*, ENSTA ParisTech (2nd year).
- *Propagation dans les guides d'ondes*, ENSTA ParisTech (3rd year) and Master "Modeling and Simulation" (M2)

Jean-François Mercier

- *Outils élémentaires d'analyse pour les équations aux dérivées partielles*, ENSTA ParisTech (1st year)
- *Fonctions d'une variable complexe*, ENSTA ParisTech, ENSTA ParisTech (2nd year)
- *Théorie spectrale des opérateurs autoadjoints et application aux guides optiques*, ENSTA ParisTech (2nd year)

9.2.2. Supervision

PhD: Antoine Tonnoir, "Simulation numérique de la diffraction d'ondes ultrasonores par un défaut localisé dans une plaque élastique anisotrope", June 2015, Anne-Sophie Bonnet-Ben Dhia and Sonia Fliss

PhD: Matthieu Lecouvez, "Méthodes de décomposition de domaine optimisées pour la propagation d'ondes en régime harmonique", July 2015, Patrick Joly and Francis Collino

PhD: Simon Marmorat, "Etude d'un modèle asymptotique et de son couplage avec une approche par éléments finis pour simuler la propagation d'ondes ultrasonores dans un milieu complexe perturbé par de petites inclusions", November 2015, Patrick Joly and Xavier Claeys

PhD: Camille Carvalho, "Étude théorique et numérique de guides d'ondes plasmoniques", December 2015, Anne-Sophie Bonnet-Ben Dhia and Patrick Ciarlet

PhD in progress : Zouhair Adnani , "Modélisation numérique tridimensionnelle des effets de site en interaction sol-structure par une méthode adaptée aux problèmes sismiques de très grande taille", October 2014, Marc Bonnet and Stéphanie Chaillat

PhD in progress : Marc Bakry, "Estimateurs a posteriori pour la résolution des problèmes de diffraction par équations intégrales", October 2013, Patrick Ciarlet and Sébastien Pernet.

PhD in progress : Geoffrey Beck, "Modélisation de la propagation d'ondes électromagnétiques dans des câbles co-axiaux", October 2012, Patrick Joly

PhD in progress : Antoine Bensalah, "Une approche nouvelle de la modélisation mathématique et numérique en aéroacoustique par les équations de Goldstein et applications en aéronautique", October 2014, Patrick Joly and Jean-François Mercier

PhD in progress : Mathieu Chamaillard, "Conditions aux limites effectives pour des revêtements minces périodiques", October 2011, Patrick Joly and Houssem Haddar

PhD in progress : Rémi Cornaggia, "Asymptotique petit-défaut de fonctions-coût et son application en identification: justifications théorique et expérimentale, extensions", October 2012, Marc Bonnet and Bojan Guzina

PhD in progress : Luca Desiderio, "Efficient visco-eleastic wave propagation in 3D for high contrast media", October 2013, Stéphanie Chaillat and Patrick Ciarlet

PhD in progress : Léandre Giret, "Development of a domain decomposition method on non-conforming meshes: application to the modeling of a Reactivity-Initiated Accident (RIA) in a Pressurized Water Reactor (PWR)", October 2014, Patrick Ciarlet

PhD in progress : Laure Pesudo , "Modélisation de la réponse ultrasonore de défauts de type fissure par méthode BEM et couplage à un modèle de propagation - Application à la simulation des contrôle non destructifs", October 2014, Marc Bonnet and Stéphanie Chaillat

PhD in progress : Arnaud Recocquillay, "Identification de défauts dans un guide d'ondes en régime temporel", October 2014, Laurent Bourgeois

PhD in progress : Elizaveta Vasilevskaia, "Modes localisés dans les guides d'onde quantiques", November 2012, Patrick Joly

PhD in progress : Valentin Vinoles, "Analyse asymptotique des équations de Maxwell en présence de métamatériaux", October 2012, Sonia Fliss and Patrick Joly

PhD in progress : Emmanuel Zerbib , "Eléments finis spectraux sur maillages décalés en électromagnétisme pour la simulation de grands modèles", October 2014, Gary Cohen

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] C. CARVALHO. *Mathematical and numerical study of plasmonic structures with corners*, ENSTA ParisTech, December 2015, https://pastel.archives-ouvertes.fr/tel-01240904

[2] S. MARMORAT. *Asymptotic models and numerical simulation for time domain wave scattering by small defects*, Université Paris-Saclay, November 2015, https://pastel.archives-ouvertes.fr/tel-01243663

[3] A. TONNOIR. *Transparent conditions for the diffraction of elastic waves in anisotropic media*, ENSTA ParisTech, June 2015, https://pastel.archives-ouvertes.fr/tel-01170583

[4] A. VIGNERON. *Formulations by surface integral equations for numerical simulation of non-destructive testing by eddy currents*, Ecole Polytechnique, January 2015, https://hal.archives-ouvertes.fr/tel-01114368

Articles in International Peer-Reviewed Journals

[5] M. BONNET, W. AQUINO. *Three-dimensional transient elastodynamic inversion using anerror in constitutive relation functional*, in "Inverse Problems", 2015, vol. 31, 035010 [*DOI :* 10.1088/0266-5611/31/3/035010], https://hal.archives-ouvertes.fr/hal-01116708

[6] M. BONNET. *Solvability of a Volume Integral Equation Formulation for Anisotropic Elastodynamic Scattering*, in "Journal of Integral Equations and Applications", 2015, forthcoming, https://hal.archives-ouvertes.fr/hal-01246135

[7] M. BONNET, A. BUREL, M. DURUFLÉ, P. JOLY. *Effective transmission conditions for thin-layer transmission problems in elastodynamics. The case of a planar layer model*, in "ESAIM: Mathematical Modelling and Numerical Analysis", 2016, vol. 50, pp. 43-75 [*DOI :* 10.1051/M2AN/2015030], https://hal.archives-ouvertes.fr/hal-01144401

[8] A.-S. BONNET-BEN DHIA, L. CHESNEL, S. NAZAROV. *Non-scattering wavenumbers and far field invisibility for a finite set of incident/scattering directions*, in "Inverse Problems", March 2015, https://hal.archives-ouvertes.fr/hal-01109534

[9] A.-S. BONNET-BEN DHIA, S. FLISS, C. HAZARD, A. TONNOIR. *A Rellich type theorem for the Helmholtz equation in a conical domain*, in "Comptes Rendus Mathématique", December 2015 [*DOI :* 10.1016/J.CRMA.2015.10.015], https://hal-ensta.archives-ouvertes.fr/hal-01160242

[10] A.-S. BONNET-BEN DHIA, É. LUNÉVILLE, Y. MBEUTCHA, S. NAZAROV. *A method to build non-scattering perturbations of two-dimensional acoustic waveguides*, in "Mathematical Models & Methods in Applied Sciences", 2015 [*DOI :* 10.1002/MMA.3447], https://hal.archives-ouvertes.fr/hal-01225313

[11] A.-S. BONNET-BEN DHIA, S. NAZAROV, J. TASKINEN. *Underwater topography invisible for surface waves at given frequencies*, in "Wave Motion", September 2015, vol. 57 [*DOI :* 10.1016/J.WAVEMOTI.2015.03.008], https://hal.inria.fr/hal-01114632

[12] E. BÉCACHE, L. BOURGEOIS, L. FRANCESCHINI, J. DARDÉ. *Application of mixed formulations of quasi-reversibility to solve ill-posed problems for heat and wave equations: the 1d case*, in "Inverse Problems and Imaging", 2015 [*DOI :* 10.3934/IPI.2015.9.971], https://hal.archives-ouvertes.fr/hal-01235099

[13] E. BÉCACHE, P. JOLY, M. KACHANOVSKA, V. VINOLES. *Perfectly matched layers in negative index metamaterials and plasmas*, in "ESAIM: Proceedings", March 2015, vol. 50, pp. 113-132 [*DOI :* 10.1051/PROC/201550006], https://hal.archives-ouvertes.fr/hal-01082445

[14] S. CHAILLAT, F. COLLINO. *A Wideband Fast Multipole Method for the Helmholtz Kernel: Theoretical Developments*, in "Computers and Mathematics with Applications", May 2015, forthcoming [*DOI :* 10.1016/J.CAMWA.2015.05.019], https://hal.archives-ouvertes.fr/hal-01154119

[15] S. CHAILLAT, M. DARBAS, F. LE LOUËR. *Approximate local Dirichlet-to-Neumann map for three-dimensional time-harmonic elastic waves*, in "Computer Methods in Applied Mechanics and Engineering", September 2015, vol. 297, n^o 1, pp. 62–83 [*DOI :* 10.1016/J.CMA.2015.08.013], https://hal.archives-ouvertes.fr/hal-01187242

[16] P. CIARLET. *On the approximation of electromagnetic fields by edge finite elements. Part 1: Sharp interpolation results for low-regularity fields*, in "Computers and Mathematics with Applications", 2016 [*DOI :* 10.1016/J.CAMWA.2015.10.020], https://hal.archives-ouvertes.fr/hal-01176476

[17] P. G. CIARLET, P. CIARLET, S. SAUTER, C. SIMIAN. *Intrinsic Finite Element Methods for the Computation of Fluxes for Poisson's Equation*, in "Numerische Mathematik", 2015, 30 p. [*DOI :* 10.1007/S00211-015-0730-9], https://hal.inria.fr/hal-01160896

[18] M.-L. CORDERO, A. MAUREL, J. F. MERCIER, S. FELIX, F. BARRA. *Tuning the wavelength of spoof plasmons by adjusting the impedance contrast in an array of penetrable inclusions*, in "Applied Physics Letters", 2015, vol. 107 [*DOI :* 10.1063/1.4929497], https://hal.inria.fr/hal-01235295

[19] G. DELGADO, M. BONNET. *The topological derivative of stress-based cost functionals in anisotropic elasticity*, in "Computers and Mathematics with Applications", 2015, vol. 69, pp. 1144-1166 [*DOI :* 10.1016/J.CAMWA.2015.03.010], https://hal.archives-ouvertes.fr/hal-00950107

[20] M. I. DIAZ, W. AQUINO, M. BONNET. *A modified error in constitutive equation approach for frequency-domain viscoelasticity imaging using interior data*, in "Computer Methods in Applied Mechanics and Engineering", 2015, vol. 296, pp. 129-149 [*DOI :* 10.1016/J.CMA.2015.07.025], https://hal.archives-ouvertes.fr/hal-01183511

[21] S. FELIX, A. MAUREL, J. F. MERCIER. *Improved multimodal method for the acoustic propagation in waveguides with finite wall impedance*, in "Wave Motion", 2015, vol. 54, 10 p. [*DOI :* 10.1016/J.WAVEMOTI.2014.11.007], https://hal.inria.fr/hal-01235285

[22] S. FELIX, A. MAUREL, J. F. MERCIER. *Wave propagation in a waveguide containing restrictions with circular arc shape*, in "Journal of the Acoustical Society of America", 2015, vol. 137, n^o 3, 7 p. [*DOI :* 10.1121/1.4913506], https://hal.inria.fr/hal-01235292

[23] S. FLISS, P. JOLY. *Solutions of the time-harmonic wave equation in periodic waveguides : asymptotic behaviour and radiation condition*, in "Archive for Rational Mechanics and Analysis", June 2015 [*DOI :* 10.1007/S00205-015-0897-3], https://hal.inria.fr/hal-01086033

[24] C. LANGRENNE, A. GARCIA, M. BONNET. *Solving the hypersingular boundary integral equation for the Burton and Miller formulation*, in "Journal of the Acoustical Society of America", 2015, vol. 138, n^o 3332-3340 [*DOI :* 10.1121/1.4935134], https://hal.archives-ouvertes.fr/hal-01233994

[25] B. LOMBARD, J. F. MERCIER, O. RICHOUX. *Numerical investigation of acoustic solitons*, in "Proceedings of the Estonian Academy of Sciences ", 2015, vol. 64, n^o 3, pp. 304-310, https://hal.archives-ouvertes.fr/hal-01091411

[26] A. MAUREL, J. F. MERCIER, S. FELIX. *Modal method for 2D wave propagation in heterogeneous anisotropic media*, in "Journal of the Optical Society of America", 2015, vol. 32, n^o 5, 11 p. [*DOI :* 10.1364/JOSAA.32.000979], https://hal.inria.fr/hal-01235291

[27] O. RICHOUX, B. LOMBARD, J. F. MERCIER. *Numerical investigation of acoustical solitons*, in "Proceedings of the Estonian Academy of Sciences ", 2015, vol. 64, n^{o} 3, 7 p. [*DOI :* 10.3176/PROC.2015.3.15], https://hal.inria.fr/hal-01235297

[28] O. RICHOUX, B. LOMBARD, J.-F. MERCIER. *Generation of acoustic solitary waves in a lattice of Helmholtz resonators*, in "Wave Motion", 2015, vol. 56, pp. 85-99 [*DOI :* 10.1016/J.WAVEMOTI.2015.02.005], https://hal.archives-ouvertes.fr/hal-01069252

[29] Q. T. TRINH, S. MOUHOUBI, C. CHAZALLON, M. BONNET. *Solving multizone and multicrack elastostatic problems: a fast multipole symmetric Galerkin boundary element method approach*, in "Engineering Analysis with Boundary Elements", 2015, vol. 50, pp. 486-495 [*DOI :* 10.1016/J.ENGANABOUND.2014.10.004], https://hal.archives-ouvertes.fr/hal-01082068

Research Reports

[30] L. BARATCHART, L. BOURGEOIS, J. LEBLOND. *Uniqueness results for 2D inverse Robin problems with bounded coefficient*, Inria Sophia Antipolis ; Inria Saclay ; Inria, January 2015, n^{o} RR-8665, Travail relié à la pré-publication du même titre, hal-01084428, November 2014.On présente ici les résultats dans un cadre plus simple et avec des preuves différentes, https://hal.inria.fr/hal-01104629

[31] S. CHAILLAT, F. COLLINO. *A Wideband Fast Multipole Method for the Helmholtz kernel: Theoretical developments*, Inria Saclay ; Inria, March 2015, n^{o} RR-8692, 28 p. , https://hal.inria.fr/hal-01121687

Other Publications

[32] V. BARONIAN, A.-S. BONNET-BEN DHIA, S. FLISS, A. TONNOIR. *Iterative methods for scattering problems in unbounded elastic waveguides*, June 2015, working paper or preprint, https://hal.inria.fr/hal-01164794

[33] A.-S. BONNET-BEN DHIA, C. CARVALHO, L. CHESNEL, P. CIARLET. *On the use of Perfectly Matched Layers at corners for scattering problems with sign-changing coefficients*, November 2015, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01225309

[34] C. CALDINI-QUEIROS, B. DESPRÉS, L.-M. IMBERT-GÉRARD, M. KACHANOVSKA. *A numerical study of the solution of x-mode equations around the hybrid resonance* , February 2015, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01114791

[35] P. CIARLET, M. VOHRALÍK. *Robust a posteriori error control for transmission problems with sign-changing coefficients using localization of dual norms*, May 2015, working paper or preprint, https://hal.inria.fr/hal-01148476

[36] G. COHEN, S. PERNET. *High order finite element methods for wave equations*, 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01253166

[37] A. TONNOIR. *Dirichlet-to-Neumann operator for diffraction problems in stratified anisotropic acoustic waveguides*, December 2015, working paper or preprint, https://hal.inria.fr/hal-01195869