Activity Report 2014

Project-Team POEMS

Wave propagation: mathematical analysis and simulation

RESEARCH CENTER
Saclay - Île-de-France

THEME
Numerical schemes and simulations

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Project-Team POEMS

Keywords: Waves, Simulation, Numerical Methods, Finite Elements, Inverse Problem

Creation of the Project-Team: 2005 January 01.

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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 conception, the analysis, the numerical approximation and the control of mathematical models for the description of wave propagation in mechanics, physics and engineering sciences.

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

- the development of an expertise relative to various types of waves (acoustic, elastic, electromagnetic, gravity waves, ...), 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 resolution of complex wave propagation problems close to real applications still poses (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 conception of new numerical methods, more and more accurate and high performing.
- The development of artificial transparent boundary conditions for handling unbounded propagation domains.
- The treatment of more and more complex problems (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 or interfaces, small homogeneities, homogenization, ...).
- The development and the analysis of algorithms for inverse problems (in particular for inverse scattering problems) and imaging techniques, using 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 which behave as a material with negative physical parameters, metals which have a negative dielectric permittivity at optical frequencies, magnetized plasmas which present a strongly anisotropic permittivity tensor with eigenvalues of different signs. 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

One 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 layers 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 either 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 an old 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 a Fast Multipole Boundary Element Method (FM-BEM) for elastodynamics, for applications to soil-structure interaction or seismology.

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 EADS and Airbus. The final objective is to reduce the noise radiated by Airbus planes. Musical acoustics constitute a particularly attractive application. We are concerned by the simulation of musical instruments whose objectives are 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.

Finally, the simulation electromagnetic (possibly complex, even fractal) networks is motivated by non-destructive testing applications. This topic is developed in partnership with CEA-LIST.

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 applications (soil-structure interaction for civil engineering, seismology).

5. New Software and Platforms

5.1. Software

5.1.1. XLiFE++

Participants: Eric Lunéville, Nicolas Kielbasiewicz, Colin Chambeyron.

XLIFE++ is a Finite Element library in C++ based on philosophy of the previous library MELINA in Fortran but with new capabilities (boundary elements, discontinuous Galerkin methods, more integrated tools -in particular mesh tools - and high performance computing skills, multithread and GPU computation). It is licensed under LGPL and developed in the context of the European project SIMPOSIUM (FP7/ICT, leader CEA/LIST, from september 2011 to august 2014). There are also academic partners: IRMAR, University of Rennes and LAMA, University of Marne-la-Vallée.

After 3 years of work, the development of the finite element library XLIFE++ reached a milestone in 2014 with the first downloadable public release, after an important effort to improve the user interface and to complete the last major developments necessary for this output: essential boundary conditions, mesh construction, Dirichlet-to-Neumann maps ... among others. In June 2014, a day was organized to present to a wider audience the features of this library. We now provide support to the users (patches, new developments...).

5.1.2. COFFEE

Participant: Stéphanie Chaillat.

COFFEE is a 3D BEM-accelerated FMM solver for linear elastodynamics (full implementation, 30 000 lines of Fortran 90). The 3-D elastodynamic equations are solved with the boundary element method accelerated by the multi-level fast multipole method. The fundamental solutions for the infinite space are used in this implementation. A boundary element-boundary element coupling strategy is also implemented so multi-region problems (strata inside a valley for example) can be solved.

6. New Results

6.1. Wave propagation in non classical media

6.1.1. Plasmonic black-hole waves at corners of metals

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 from CMAP at Ecole Polytechnique. We study the scattering of time-harmonic electromagnetic waves by a metallic obstacle in a 2D setting, at frequencies such that the dielectric permittivity of the metal has a negative real part and a small imaginary part. When the obstacle has corners, due to the sign-changing real part of the permittivity, unusual strong singularities for the electromagnetic field can appear. If the material dissipation is neglected, it can be necessary to consider a new functional framework, containing these singularities, to derive a well-posed problem. In this new framework, everything happens like if plasmonic waves were propagating to the corners, and a part of the energy is trapped by the corner, even if the material has been supposed non-dissipative. We have implemented an original numerical method consisting in using Perfectly Matched Layers at the corners to capture these black-hole waves. We have also proposed a new rule to mesh the corner in order to achieve convergence of classical finite elements in the simpler case where the problem is still well-posed in the classical framework. Finally, in collaboration with André Nicolet and Frédéric Zolla from Institut Fresnel in Marseille, we are now considering realistic dissipative metals. We show that there is still a significant effect of the black-hole phenomenon, which results in an unusual energy leakage in some frequency range.

6.1.2. Limiting amplitude principle for a two-layered dielectric/metamaterial medium

Participants: Maxence Cassier, Christophe Hazard, Patrick Joly.

This work has been a part of the PhD of Maxence Cassier and has allowed to initiate a collaboration with Boris Gralak from Institut Fresnel. For wave propagation phenomena, the limiting amplitude principle holds if the time-harmonic regime represents the large time asymptotic behavior of the solution of the evolution problem with a time-harmonic excitation. Considering a two-layered medium composed of a dielectric material and a Drude metamaterial separated by a plane interface, we prove that the limiting amplitude principle holds except for a critical situation related to a surface resonance phenomenon. Then the solution can either converge to the superposition of two time-periodic fields, or blow up linearly in time.

6.1.3. Perfectly Matched Layers in plasmas and metamaterials

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

This work is a part of the PhD of Valentin Vinoles and is the subject of the post-doc of Maryna Kachanovska. It deals with the stability of Perfectly Matched Layers (PMLs) in dispersive media and is motivated by the fact that classical PMLs are unstable in negative index metamaterials and in some anisotropic plasmas. This led us to derive a new necessary criterion of stability which is valid for a large class of dispersive models and for more general PMLs than the classical ones. This criterion has been used to design new stable PMLs for negative index metamaterials and uniaxial anisotropic plasmas.

6.1.4. Retrieval method for anisotropic metamaterials

Participants: Aurore Castanié, Jean-François Mercier.

This work has been done during the post-doc of Aurore Castanié, in collaboration with Agnès Maurel from Institut Langevin at ESPCI and Simon Felix from the LAUM (Laboratoire d'Acoustique de l'Université du Maine). Electromagnetic or acoustic metamaterials can be described in terms of equivalent effective, in general anisotropic, media and several techniques exist to determine the effective permeability and permittivity (or effective mass density and bulk modulus in the context of acoustics). Among these techniques, retrieval methods use the measured scattering coefficients for waves incident on a metamaterial slab containing few unit cells. Until now, anisotropic effective slabs have been considered in the literature but they are limited to the case where one of the axes of anisotropy is aligned with the slab interface. We propose an extension to arbitrary orientations of the principal axes of anisotropy and oblique incidence. The retrieval method is illustrated in the electromagnetic case for layered media, and in the acoustic case for array of tilted elliptical particles.

6.2. Wave propagation in heterogeneous media

6.2.1. 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 requires to solve cell problems in infinite strips.

6.2.2. Multiple scattering by small homogeneities

Participants: Patrick Joly, Simon Marmorat.

This is the topic of the PhD of Simon Marmorat, done in collaboration with the CEA-LIST and with Xavier Claeys (LJLL, Paris VI). We aim at developing 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. This kind of problem is very costly to handle with classical numerical methods, due the refined meshes needed around the inclusions. To overcome these issues, two models have been developed, which rely on the asymptotic analysis of the problem: each of them can be interpreted as a full space wave equation, which can be discretized using a defects-free mesh, coupled to some auxiliary unknowns accounting for the presence of the inclusions. While the first model is established by using a special Galerkin approximation in the vicinity of the inclusions, the second model only focuses on the far field. The challenge is then to simulate source points coupled to the incident field and this is achieved thanks to the introduction of a special relaxed version of the Dirac mass. Rigorous error estimates as well as some numerical tests have been established, highlighting the efficiency of the two methods.

6.2.3. Finite Element Heterogeneous Multiscale Method for Maxwell's Equations

Participants: Patrick Ciarlet, Sonia Fliss, Christian Stohrer.

This work is the subject of the post-doc of Christian Stohrer. The standard Finite Element Heterogeneous Multiscale Method (FE-HMM) can be used to approximate the effective behavior of solutions to the classical Helmholtz equation in highly oscillatory media. Using a novel combination of well-known results about FE-HMM and the notion of T-coercivity, we derive an a priori error bound. Numerical experiments corroborate the analytical findings. We work now on the application of HMM in presence of interfaces, for Maxwell's equations and finally in presence of high contrast materials.

6.2.4. Effective boundary conditions for strongly heterogeneous thin layers

Participants: Matthieu Chamaillard, Patrick Joly.

This topic is the object of the PhD of Matthieu Chamaillard, done in collaboration with Houssem Haddar (CMAP École Polytechnique). 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. In the scalar case, we proved that the error between the exact model (with the thin coat) and the one with the effective boundary condition of order n for $n \in \{1,2\}$ is of the order $\mathcal{O}(\delta^{n+1})$. This has been checked numerically for some two dimensional configurations. Recently, we also succeeded to extend our theoretical work to Maxwell equations. We found a first order boundary condition of the form $E \times n = \delta ik \mathcal{Z}_\Gamma\left(n \times (H \times n)\right)$ where n is the unit outward normal to the boundary Γ and $\mathcal{Z}_\Gamma$ is a second order tangential differential operator along Γ. The coefficients of this operator depend only on the deformation mapping ψ_Γ and the material properties of the coating, through the resolution of particular unbounded cell problems in the flat reference configuration. When the coating is homogeneous, one recovers the well known first order thin layer condition. We have moreover proven that this effective condition provides an error of the order $\mathcal{O}(\delta^2)$.

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, Elizaveta Vasilevskaya.

This work is done in the context of the PhD of Elizaveta Vasilevskaya, in collaboration with Bérangère Delourme, from Paris 13 University. We consider the theoretical and numerical aspects of the wave propagation in ladder-like periodic structures. We exhibit situations where the introduction of a lineic defect into the geometry of the domain leads to the appearance of guided modes and we provide numerical simulations to illustrate the results. 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. Numerical computations are based on specific transparent conditions for periodic media.

6.3.2. Absence of trapped modes for a class of unbounded propagative media

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

We have proposed a new approach to prove that there does not exist square-integrable solutions to the two-dimensional Helmholtz equation in a homogeneous conical domain with a vertex angle greater than π. This shows that for a medium filling the whole plane, there can be no trapped modes if all the inhomogeneities (penetrable or not) are concentrated in a conical domain with a vertex angle less than π. The proof uses the compatibility of Fourier representations of the field in different half-spaces. One interesting consequence of our result concerns the case of curved open waveguides (e.g., bended optical fibers). Unlike closed waveguides for which trapped modes confined near the bend may occur, our result implies that trapped modes cannot exist if the core of the waveguide is located in a cone with vertex angle less than π. Our results can be extended to higher space dimensions, and to some Y-junctions of open waveguides (using a generalized Fourier transform instead of the usual one).

6.3.3. 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 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 is 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 quantum graph in which, along each edge, one is reduced to compute the electrical potential and current by solving 1D wave equations (the telegrapher's model) coupled by vertex conditions. Using the method of matched asymptotics, we have derived and justified improved Kirchhoff conditions.

6.3.4. Geometrical transformations for waveguides of complex shapes

Participant: Jean-François Mercier.

In collaboration with Agnès Maurel from the Langevin Institut and Simon Felix from the LAUM, we have developed multimodal methods to describe the acoustic propagation in rigid waveguides of general shapes, with varying curvature and cross section. A key feature is the use of a flexible geometrical transformation to a virtual space in which the waveguide is straight but associated to Robin boundary conditions. We have revisited an efficient method developed earlier which consists in adding two extra non-physical modes to the usual modal expansion of the field on the Neumann guided modes, in order to obtain a better convergence of the modal series.

This method has been extended to a half guide with an end wall of general shape, transformed into a flat surface by a geometrical transformation, thus avoiding to question the Rayleigh hypothesis. The transformation only affects a bounded inner region that naturally matches the outer region, which allows to easily select the ingoing and outgoing waves.

6.4. Inverse problems

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

Participants: Eliane Bécache, Laurent Bourgeois.

This work is a collaboration with Jérémi Dardé from Toulouse University and has been the object of the internship of Lucas Franceschini, student at ENSTA. We address some linear ill-posed problems involving the heat or the wave equation, in particular the backward heat equation and the heat/wave equation with lateral Cauchy data. The main objective is to introduce some 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 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 in all those situations.

6.4.2. Uniqueness and non-uniqueness results for the inverse Robin problem

Participant: Laurent Bourgeois.

This work is a collaboration with Laurent Baratchart and Juliette Leblond (Inria, APICS). We consider the classical Robin inverse problem, which consists in finding the ratio between the normal derivative and the trace of the solution (the Robin coefficient) on a subset of the boundary, given the Cauchy data (both the normal derivative and the trace of the solution) on the complementary subset. More specifically, we consider a Robin coefficient which is merely in L^∞ and a Neumann data in L^2. In the $2D$ case we prove uniqueness of the Robin coefficient for a problem governed in a Lipschitz domain by a conductivity equation with a conductivity chosen in $W^{1,r}$, where $r > 2$. We also prove a non-uniqueness result in the $3D$ case. In two dimensions, the proof relies on complex analysis, while in higher dimension, the proof relies on a famous counterexample to unique continuation by Bourgain and Wolff.

6.4.3. 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 defect identification by time-harmonic elastodynamic measurements. We propose a generalization to higher orders of the concept of topological derivative, by expanding the least-squares functional in powers of the small radius of a trial inclusion. This expansion is facilitated by resorting to an adjoint state. With this approach, a region of interest may be exhaustively probed at reasonable computational cost.

6.4.4. Inverse scattering and invisibility with a finite set of emitted-received waves

Participant: Anne-Sophie Bonnet-Ben Dhia.

In collaboration with Lucas Chesnel from CMAP at Ecole Polytechnique and Sergei Nazarov from Saint-Petersburg University, we investigate a time harmonic acoustic scattering problem by a compactly supported penetrable inclusion in the free space. We consider cases where an observer can produce incident plane waves and measure the far field pattern of the resulting scattered field only in a finite set of directions. In this context, we say that a wavenumber is a non-scattering wavenumber if the associated relative scattering matrix has a non trivial kernel. Under certain assumptions on the physical coefficients of the inclusion, we have shown that the non-scattering wavenumbers form a (possibly empty) discrete set. Then, for a given real wavenumber, we built a constructive technique (which provides a numerical algorithm) to prove that there exist inclusions for which the corresponding relative scattering matrix is null. These inclusions have the important property to be impossible to detect from far field measurements.

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

Participant: Marc Bonnet.

This work is a collaboration with Wilkins Aquino (Duke University, USA). It is concerned with large-scale three-dimensional inversion under transient elastodynamic conditions by means of the modified error in constitutive relation (MECR), an energy-based, cost functional. Each evaluation of a time-domain MECR cost functional involves the solution of 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 an approach whose main ingredients are (a) setting the entire computational procedure in a consistent time-discrete framework that incorporates the chosen time-stepping algorithm, and (b) using 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.

6.5. Integral equations

6.5.1. Fast solution of the BEM system in 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), we derive a fast direct solver for the BEM system in 3-D frequency-domain elastodynamics. We assess the numerical efficiency and accuracy on the basis of numerical results obtained for problems having known solutions. In particular, we study the efficiency of low-rank approximations when the frequency is increased. The efficiency of the method is also illustrated to study seismic wave propagation in 3-D domains. 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, and is constructed in the framework of the On-Surface Radiation Condition (OSRC) method. This OSRC-like preconditioner is successfully applied to Dirichlet exterior problems in 3D elastodynamics.

6.5.3. Boundary Integral Formulations for Modeling Eddy Current Testing

Participants: Marc Bonnet, Audrey Vigneron.

This work was a part of the PhD thesis of Audrey Vigneron, and has been done in collaboration with Edouard Demaldent from CEA-List. It concerns the simulation of eddy current non-destructive testing, which aims to assess the presence of defects (cut, corrosion ...) in a conductive, and possibly magnetic, medium. We propose a simple block-SOR solution method for the PMCHWT-type Maxwell integral formulation, that is well suited for the low-frequency, high-conductivity limit typical of eddy current testing methods. We also derive an asymptotic expansion of the Maxwell integral formulation in powers of some relevant (small) non-dimensional number and show its relation to Hiptmair's eddy current integral formulation. Both aspects are validated on 3D numerical experiments.

6.6. Domain decomposition methods

6.6.1. Transparent boundary conditions with overlap in elastic waveguides

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

This work is a part of the PhD of Antoine Tonnoir and is done in partnership with Vahan Baronian form CEA-LIST. We have conceived new transparent boundary conditions for the time-harmonic diffraction problem in an acoustic or elastic waveguide. These new conditions use the natural modal decomposition in the waveguide and are said "with overlap" by analogy with the domain decomposition methods. Among their main advantages, they can be implemented in general elastic anisotropic waveguides, for which usual Dirichlet to Neumann maps are not available. Moreover, the traditional benefit of the overlap for iterative resolution is obtained, independently of the size of the overlap.

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

Participants: Patrick Joly, Matthieu Lecouvez.

This is the object of the PhD thesis of Matthieu Lecouvez in collaboration with the CEA-CESTA and Francis Collino. We are interested in the diffraction of time harmonic electromagnetic waves by perfectly conducting objects covered by multi-layered (possibly thin) dielectric coatings. This problem is computationally hard when the size of the object is large (typically 100 times larger) with respect to the incident wavelength. In such a situation, the idea is 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). We propose a practical solution that uses approximations of nonlocal integral operators with appropriate Riesz potentials.

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 particular, one must solve the neutron diffusion equation 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 DDM has been recently addressed for conforming meshes. The development of non-conforming, hence more flexible, methods is under way. Since one is dealing with highly heterogeneous configurations, the regularity of the exact solution can be very low, which then deteriorates the convergence rate of the discretized solution to the exact one. Next, the optimization of the eigenvalue loop will be studied.
This topic is developed in partnership with CEA-DEN (Erell Jamelot). Realistic computations are carried out with the APOLLO3 neutronics code.

6.7. Aeroacoustics

6.7.1. Time-harmonic acoustic scattering in a rotationnal 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 EADS. 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. Extending the proof done for the Galbrun equation, it is possible to prove that the Goldstein equations are well-posed in a domain Ω if the flow is Ω-filling (each point of Ω is reached by a streamline coming from the inflow boundary in a finite time). Then we focused on the case of a rotating flow in an annular geometry, which is not Ω-filling and we proved the well-posedness of the problem .

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-CEA-LIST
Participants: Marc Bonnet, Audrey Vigneron.

Start : 01/01/2013, End : 12/31/2015. Administrator : ENSTA.
This contract is about the modelisation of eddy current by integral equations.

Contract POEMS-CEA-LIST
Participants: Marc Bonnet, Stéphanie Chaillat, 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 : 10/01/2010, 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.

7.2. Bilateral Grants with Industry

Contract POEMS-CEA-LIST-DIGITEO
Participants: Anne-Sophie Bonnet-Ben Dhia, Sonia Fliss, Antoine Tonnoir.

Start : 10/01/2011, End : 09/30/2014. Administrator : CEA-LIST.
SIDONIE : SImulation numérique de la Diffraction d'Ondes ultrasonores par un défaut localisé dans une Plaque aNIsotropE

8. Partnerships and Cooperations

8.1. National Initiatives - ANR

- ANR project *PROCOMEDIA: Propagation d'ondes en milieux complexes*
  Partners: ESPCI, Laboratoire d'Acoutique de l'Université du Maine, Departamento de Fisica de la Universidad de Chile.
  Start : 04/01/2011, End : 03/30/2014. Administrator : CNRS. Coordinator for POEMS : Jean-François Mercier.
- 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: Université Pierre et Marie Curie (Paris 6), Université de Lorraine
  Start : 10/01/2012, End : 10/01/2015 Administrator : Inria Coordinator for POEMS: Eliane Bécache
- ANR project *SODDA: Diagnostic de défauts non francs dans les réseaux de câbles*
  Partners: CEA LIST, ESYCOM, LGEP (Supelec)
  Start : 10/01/2012, End : 10/01/2015 Administrator : Inria Coordinator for Poems: Patrick Joly
- 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

8.2. European Initiatives - FP7 & H2020 Projects

8.2.1. SIMPOSIUM

Type: FP7

Defi: ICT for the Enterprise and Manufacturing

Instrument: Integrated Project

Objectif: PPP FoF: Digital factories: Manufactoring design and product lifecycle management

Duration: September 2011 - August 2014

Coordinator: Steve MAHAUT, CEA/LIST

Inria contact: P. Joly, E. Lunéville

Abstract: Gathering together industrial companies, research centres and universities, the purpose of the SIMPOSIUM project is the integration in a unique platform of interoperable Non Destructive Evaluation simulation tools, to make possible virtual testing of parts at the early stages of manufacturing and design. The role of POEMS team is to develop a new finite element library (XLiFE++) with specific tools dedicated to propagation in waveguides. The library is now available and simulations of propagation in composite (anistropic elastic medium) waveguide have been done and compared to simulations provided by CIVA platform.

8.2.2. 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

Wilkins Aquino (Duke University)

George Biros (University of Texas, Austin)

Fioralba Cakoni (University of Delaware)

Eric Chung (Chinese University of Hong Kong)

Dan Givoli (Technion - Israel Institute of Technology)

Nabil Gmati (Ecole Nationale d'Ingénieurs de Tunis)

Bojan Guzina (University of Minnesota)

Manfred Kaltenbacher (Technische Universitat Wien)

Sergei Nazarov (Saint-Petersburg University)

Jeronimo Rodriguez (University of Santiago de Compostela)

Kersten Schmidt (Technische Universitat Berlin)

Chrysoula Tsogka (University of Crete)

Ricardo Weder (Universidad Nacional Autonoma, Mexico)

Wensheng Zhang (Institute of Computational Mathematics, Beijing)

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.

8.3.3. Visits of International Scientists

Ricardo Weder, Institute of Applied Mathematics and Systems, Universidad Nacional Autonoma, Mexico (June 2014).

Wensheng Zhang, Institute of Computational Mathematics, Beijing (September 2014).

Eric Chung, Department of Mathematics, Chinese University of Hong Kong (November 2014).

Shravan Veerapaneni, Department of Mathematics, University of Michigan (December 2014).

8.3.4. Visits to International Teams

Gary Cohen visited Prof. Wensheng Zhang at LSEC, Institute of Computational Mathematics, Chinese Academy of Sciences (CAS) in Beijing January 5-13.

Gary Cohen visited Dr. Eric Chung at Department of Mathematics in The Chinese University of Hong Kong (CUHK). They continued their collaboration on staggered discontinuous Galerkin methods and started a collaboration on mortar elements for hybrid meshes for the Maxwell's system.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Advisory and management activities

- A. S. Bonnet-Ben Dhia was the chair of the scientific council of the CNRS Institute for Engineering and Systems Sciences (INSIS) until September 2014.
- 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

- M. Bonnet was a member of the program committee of the 5th International Workshop on New Computational Methods for Inverse Problems(ENS Cachan, May 2014).
- E. Bécache, A. S. Bonnet-Ben Dhia, M. Bonnet, C. Hazard, P. Joly and E. Lunéville are members of the scientific committee for the 12th international conference on mathematical and numerical aspects of wave propagation, which will be held in Karlsruhe in July 2015.
- A. S. Bonnet-Ben Dhia is a member of the organizing committee of the workshop Waveguides: Asymptotic Methods and Numerical Analysis which will be held in Napoli in May 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 Analyses 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 DEA (Differential Equations and Applications)
- 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)

Marc Bonnet

- *Problèmes inverses*, Master DSMSC (Centrale Paris)
- *Méthodes intégrales*, Master TACS (ENS Cachan)
- *Equations intégrales et multipôles rapides*, Ecole doctorale MODES (Univ. Paris Est, Marne la Vallée)
- *Outils élémentaires d'analyse pour les équations aux dérivées partielles*, ENSTA ParisTech (1st year)

Anne-Sophie Bonnet-Ben Dhia

- *Outils élémentaires d'analyse pour les équations aux dérivées partielles*, 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).
- *Propagation d'ondes*, Ecole Centrale de Paris (3rd year) and master DSMSC.

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)

Stéphanie Chaillat

- *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA ParisTech (1st year)
- *Fonctions d'une variable complexe*, ENSTA ParisTech (2nd year)

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)

Gary Cohen

- Gary Cohen is writing a book entitled "High Order Finite Element Methods for Wave Equations" in collaboration with Sébastien Pernet (DTIM-ONERA). This book addresses construction and analysis of a large class of finite element methods and discontinuous Galerkin methods for wave equations and should be published by Springer-Verlag in Sept. 2015.

Sonia Fliss

- *Méthode des éléments finis*, ENSTA ParisTech (2nd year)
- *Programmation scientifique et simulation numérique*, 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)

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)

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 : Aliénor Burel, " Contributions à la simulation numérique en élastodynamique : découplage des ondes P et S, modèles asymptotiques pour la traversée de couches minces", July 2014, Patrick Joly and Marc Bonnet

PhD : Maxence Cassier, "Etude de deux problèmes de propagation d'ondes transitoires : 1) Focalisation spatio-temporelle en acoustique ; 2) Transmission entre un diélectrique et un métamatériau", Juin 2014, Christophe Hazard and Patrick Joly

PhD : Audrey Vigneron, "Formulations intégrales pour la simulation du contrôle non destructif par courants de Foucault", January 2015, Marc Bonnet

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, Marc Lenoir 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 : Camille Carvalho, "Étude théorique et numérique de guides d'ondes plasmoniques", October 2012, Anne-Sophie Bonnet-Ben Dhia and Patrick Ciarlet

PhD in progress : Matthieu 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 nonconforming meshes: application to the modeling of a Reactivity-Initiated Accident (RIA) in a Pressurized Water Reactor (PWR)", October 2014, Patrick Ciarlet

PhD in progress : Matthieu Lecouvez, "Méthodes de décomposition de domaine optimisées pour la propagation d'ondes en régime harmonique", March 2012, Patrick Joly

PhD in progress : 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", Mars 2012, Patrick Joly

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 : Antoine Tonnoir, "Simulation numérique de la diffraction d'ondes ultrasonores par un défaut localisé dans une plaque élastique anisotrope", October 2011, Anne-Sophie Bonnet-Ben Dhia and Sonia Fliss

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

9.3. Popularization

- Publication in the journal Interstices of Inria: *Le piano rêvé des mathématiciens* Juliette Chabassier, Antoine Chaigne, Marc Duruflé and Patrick Joly.
- Conference of Patrick Joly to high school teachers:*Modélisation d'instruments de musique par ordinateur*, Journées ISN pour l'académie de Versailles, Inria Rocquencourt, April 2014.
- Conference of Patrick Joly to high school students during the TFJM (Tournoi Français des Jeunes Mathématiciens et Mathématiciennes) at ENSTA, June 2014.

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] A. BUREL. *Numerical methods for elastic wave propagation : P and S wave decoupling, asymptotic models for thin layers*, Université Paris Sud - Paris XI, July 2014, https://tel.archives-ouvertes.fr/tel-01060178

[2] M. CASSIER. *Analysis of two wave propagation phenomena: 1) Space-time focusing in acoustics; 2) Transmission between a dielectric and a metamaterial.*, Ecole Polytechnique X, June 2014, https://pastel.archives-ouvertes.fr/pastel-01023289

[3] 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

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