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Activity Report 2012

Project-Team POEMS

Wave propagation: mathematical analysis and simulation

IN COLLABORATION WITH: Propagation des ondes : étude mathématique et simulation (POEMS)

RESEARCH CENTER
Saclay - Île-de-France

THEME
Computational models and simulation

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Project-Team POEMS

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2. Overall Objectives

2.1. Introduction

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

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

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

The project POEMS is an UMR (Unité Mixte de Recherche) between CNRS, ENSTA and Inria (UMR 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, ...) and in particular for their numerical simulation,
- the treatment of complex problems whose simulation is close enough to real life situations and industrial applications,
- the development of original mathematical and numerical techniques,
- the development of computational codes, in particular in collaboration with external partners (scientists from other disciplines, industry, state companies...)

2.2. Highlights of the Year

Among the significative scientific advances and successes of this year, we would like to emphasize:

- The habilitation of L. Bourgeois on various imverse problems governed by elliptic equations.
- The PhD thesis of J. Chabassier on the numerical simulation of a grand piano
- The PhD thesis of L. Chesnel on the analysis of dign changing transmission coefficients with applications to electromagnetic metamaterials.
- Three new ANR Projects : CHROME on electromagnetic wave propagation in fusion plasmas, SODDA on the non destructive testing of networks of electric cables and RAFFINE about a posteriori estimators for integral equations.

3. Scientific Foundations

3.1. Mathematical analysis and simulation of wave propagation

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

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

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

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

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

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

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

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

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

4. Application Domains

4.1. Introduction

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

4.2. Acoustics

As the acoustic propagation in a fluid at rest can be described by a scalar equation, it is generally considered by applied mathematicians as a simple preliminary step for more complicated (vectorial) models. However, several difficult questions concerning coupling problems have occupied our attention recently. Aeroacoustics, or more precisely, acoustic propagation in a moving compressible fluid, is for our team a new and very challenging topic, which gives rise to a lot of open questions, from the modeling (Euler equations, Galbrun equations) to the numerical approximation of such models (which poses new difficulties). Our works in this area are partially supported by EADS and Airbus. The typical objective is to reduce the noise radiated by Airbus planes. Vibroacoustics, which concerns the interaction between sound propagation and vibrations of thin structures, also raises up a lot of relevant research subjects.

Both applications (Aeroacoustics and Vibroacoustics) led us in particular to develop an academic research between volumis methods and integral equations in time domain.

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

4.3. Electromagnetism

This is a particularly important domain, first because of the very important technological applications but also because the treatment of Maxwell's equations is much more technically involved from the mathematical point of view that the scalar wave equation. Applied mathematics for electromagnetism during the last ten years have mainly concerned stealth technology, electromagnetic compatibility, design of optoelectronic micro-components or smart materials. Stealth technology relies in particular on the conception and simulation of new absorbing materials (anisotropic, chiral, non-linear...). The simulation of antennas raises delicate questions related to the complexity of the geometry (in particular the presence of edges and corners). In optics, the development of the Mmcro and nano optics has made recently fantastic progress and the thematic of metamaterials (with negative index of refraction) opens new amazing applications. For all these reasons, we are developing an intense research in the following areas

- Highly accurate and hybrid numerical methods in collaboration with CEA (Gramat) and ONERA (Toulouse).
- Electromagmetic wave propagation in periodic media.
- Development of simplified approximate models by asymptotic anslysis for various applications : boundary layers, thin coatings, thin domains, thin wires and cables, ...
- Mathematical and numerical questions linked to the modeling of metamaterials.

4.4. Elastodynamics

Wave propagation in solids is with no doubt, among the three fundamental domains that are acoustics, electromagnetism and elastodynamics, the one that poses the most significant difficulties from mathematical and numerical points of view.

Our activity on this topic began with applications in geophysics, which unfortunately has been forced to slow down in the middle of the 90's due to the disengagement of French oil companies in matter of research. However it has seen a most welcomed rebound through new academic problems (in parficular surface waves, perfectly matched layers techniques, inverse problems in wave guides) and industrial contacts, more precisely with CEA-LIST with which we have developed a long term collaboration in the domain of non destructive testing by ultrasounds. The most recent problems we have been dealing with in this domain concern elastic wave propagation in plates, the modeling of piezoelectric devices or elastic wave propagation in highly heterogeneous media.

5. Software

5.1. Introduction

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

5.2. XLIFE++

XLIFE++ is a new Finite Element library in C++ based on philosophy of the previous library MELINA in Fortran but with new capabilities (boundary element, discontinuous Galerkin methods, more integrated tools (in particular mesh tools) and high performance computing skills (multihread and GPU computation). It is licensed under LGPL and it is developped 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-univ. Rennes and Lama-univ. Paris-Est .

In 2012, all development tools have been set up : versioning using Git, repository on Inria-Gforge, compiling and installing tools using Cmake, documentation in TeX and using Doxygen), test processing. All fundamentals library have been developped and checked (String, Function, Messages, Matrix, Vector, ...) and major libraries are done : geometry (Mesh description and tools), space,form, operators to deal with variational descriptions of PDE problem, finiteElements describing all finite elements description, term wich deals with sparse matrix representation of linear or bilinear forms involved in variational problems and finally the solvers library. A first version of the library should be published soon.

6. New Results

6.1. Numerical methods for time domain wave propagation

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

Participant: Patrick Joly.

This topic is developed in collaboration with J. Rodriguez (Santiago de Compostela) in the framework of the contract ADNUMO with AIRBUS. The general objective was to use time-domain integral equations - or retarded potentials - as a tool for contructing transparent boundary conditions for wave problems in unbounded media, by coupling them to an inerior volumic method, namely the Discontinuous Galerkin (DG) method.

Since last year, our new goal is to extend the method proposed in a previous work for DG with central fluxes to the case of upwind fluxes, while preserving most of the good properties of the original method from both theoretical (stability via energy dissipation - instead of energy conservation) and practical points of view. We have designed a method that achieves this goal at the only prize of a small deterioration of the CFL condition. The method has been successfully implemented and the numerical results clearly emphasize the superiority of upwing fluxes for taking into account the convection terms in the linearized Euler equations in aeroacoustics, the privileged application.

At the same time, we have used similar ideas for treating physical boundary conditions involving differential (in time) impedance operators.

6.1.2. Solving the Homogeneous Isotropic Linear Elastodynamics Equations Using Potentials and Finite Elements.

Participants: Aliénor Burel, Marc Duruflé, Patrick Joly.

This topic is the subject of the first part oh th PhD thesis of A. Burel. Its aim is to use the classical theoretical decomposition of the elastodynamic displacement into two potentials referring to the pressure wave and the shear wave, and use it in a numerical context. Last year, a method has been proposed for solving the Dirichlet problem (clamped boundary), successfully analyzed and implemented. For free boundary conditions, we have proposed an original method considereing these boundary conditions as a perturbation of the Dirichlet conditions. The natural adaptation of the variational formulation used in the case of the Dirichlet problems presents nice theoretical properties and leads to satisfactory numerical results for the time harmonic problem. However, the implementation for the time dependent problem reveals severe instability phenomena that seem to be already present in the semi-discrete (in space) problem. In order to understand the cause of these instability (and possibly remedy them) we are currently performing the Kreiss analysis of the half-space problems in the case where Q_1 finite elements are used on the same uniform square grid for both P-waves and S-waves potentials.

6.1.3. Time domain analysis of Maxwell's equations in Lorentz materials

Participants: Maxence Cassier, Lucas Chesnel, Christophe Hazard, Patrick Joly, Valentin Vinoles.

This is the time-domain counterpart of the research done at Poems about frequency domain analysis of metamaterials (see also the section 6.2.7) in the framework of the ANR Project Metamath. One fundamental question is the link between the two problems via the limiting amplitude principle, in particular in the cases where the time harmonic problem fails to be well posed problem in the standard framework. This occurs at certain frequencies (see section) when one considers a transmission problem between a Lorentz material and a standard one.

We are investigating this question from both theoretical and numerical points of view. This is also the object of a collaboration with B. Gralak from the Institut Fresnel in Marseille.

6.1.4. Modeling and numerical simulation of a piano.

Participants: Juliette Chabassier, Marc Duruflé, Sébastien Imperiale, Patrick Joly.

The defense of the PhD thesis of Juliette Chabassier, in March, has marked one of the most spectacular achievements in Poems for the past years, concerning the "complete" physical and mathematical modeling of a grand piano and its computer simulation. This is the result of a quite interdisciplinary work in collaboration with Antoine Chaigne (UME, ENSTA). We refer the reader to the three previous activity reports of Poems for a more detailed description of the scientific developments that have led to the implementation of a parallel code for the simulation of the piano. Using this code, M. Duruflé and J. Chabassier have realized a bank of synthetic sounds that can be used for playing scoreboards (using MIDI files for instance). For more details, and also other additional information about the work, we refer the reader to the Web page : http://modelisation.piano.free.fr.

Although already quite satiafactory, the results obtained by the present version of the code show that there is still room for the improvement of our piano model. One of the ideas consists in improving the quality of the model for the hammers and that is why J. Chabassier and M. Duruflé have proposed an enriched model involving the virations of the hammer's shank. We expect to achieve further progress in this direction through our participation to the ITN (Initial Training Network) European project BATWOMAN (Basic Acoustics Training and Workprogram on Methodologies for Acoustics Network) that has been submitted lst November. This projects regroups 11 partners from 7 different contries and gathers academic people with industrials of the donain, including Steinway.

As a theoretical complement to the numerical developments, we have led a systematic theoretical study of the numerical method used in our code for computing string's vibrations. Our concern was to develop a new implicit time discretization, which is associated with finite element methods in space, in order to reduce numerical dispersion while allowing the use of a large time step. We proposed a new θ-scheme based on different θ-approximations for the flexural and shear terms of the equations, which allows to reduce numerical dispersion while relaxing the stability condition. In particular, we gave some insights of innovative proofs of stability by energy techniques that provide uniform estimates with respect to the CFL number. Theoretical results have been illustrated with numerical experiments corresponding to the simulation of a realistic piano string.

6.1.5. Numerical methods in electromagnetism

Participant: Patrick Ciarlet.

Collaborations with Eric Chung, Tang Fei Yu and Jun Zou (Chinese University of Hong Kong, China), Philippe Ciarlet (City University of Hong Kong, China) Haijun Wu (Nanjing University, China), Stefan Sauter and Corina Simian (Universität Zürich).
The numerical approximation of electromagnetic fields is still a very active branch of research. Below, three lines of work are briefly reported.
Edge finite elements are widely used in 2D/3D electromagnetics, however they approximate very weakly the divergence of the fields. In a recent work with H. Wu & J. Zou, we proposed a method that allows one to approximate the divergence accurately in H^{-s}-norms ($1/2 < s < 1$).

Discontinuous Galerkin finite elements are also very popular, as they allow one to design fast (and accurate) methods to solve PDEs. Jointly with E. Chung and T. F. Yu, we designed a numerical method to solve the 2D/3D time-dependent Maxwell equations, using a high order staggered DG method in the spirit of those introduced by E. Chung and B. Engquist. The method has been analyzed on Cartesian meshes and its generalization to unstructured meshes is under way.
A few years ago, we proposed with Philippe Ciarlet a method to solve some problems in linear elasticity intrinsically. With S. Sauter, C. Simian and Philippe Ciarlet, we studied a similar approach that can be applied to 2D electrostatics. It consists in solving the problem in the electric field directly, using exact or local curl-free approximation of the field. Within this framework, we have been able to derive a general method that allows one to derive intrinsic conforming and non-conforming finite element spaces to compute the electrostatic potential. Generalization to 3D electrostatics and linear elasticity is under way.

6.2. Time-harmonic diffraction problems

6.2.1. Numerical computation of variational integral equation methods

Participants: Marc Lenoir, Nicolas Salles.

The dramatic increase of the efficiency of the variational integral equation methods for the solution of scattering problems must not hide the difficulties remaining for an accurate numerical computation of some influence coefficients, especially when the panels are close and almost parallel.

The formulas have been extended to double layer potentials and, for self influence coefficients, to affine basis functions. Their efficiency for the solution of Maxwell equations has been proved in the framework of a collaboration with CERFACS.

6.2.2. Formulation and Fast Evaluation of the Multipole Expansions of the Elastic Half-Space Fundamental Solutions

Participants: Marc Bonnet, Stéphanie Chaillat.

The use of the elastodynamic half-space Green's tensor in the FM-BEM is a very promising avenue for enhancing the computational performances of 3D BEM applied to analyses arising from e.g. soil-structure interaction or seismology. This ongoing work is concerned with a formulation and computation algorithm for the elastodynamic Green's tensor for the traction-free half-space allowing its use within a Fast Multipole Boundary Element Method (FM-BEM). Due to the implicit satisfaction of the traction-free boundary condition achieved by the Green's tensor, discretization of (parts of) the free surface is no longer required. Unlike the full-space fundamental solution, the elastodynamic half-space Green's tensor cannot be expressed in terms of usual kernels such as e^{ikr}/r or $1/r$. Its multipole expansion thus cannot be deduced from known expansions, and is formulated in this work using a spatial two-dimensional Fourier transform approach. The latter achieves the separation of variables which is required by the FMM. To address the critical need of an efficient quadrature for the 2D Fourier integral, whose singular and oscillatory character precludes using usual (e.g. Gaussian) rules, generalized Gaussian quadrature rules have been used instead. The latter were generated by tailoring for the present needs the methodology of Rokhlin's group. Numerical tests have been conducted to demonstrate the accuracy and numerical efficiency of the proposed FMM. In particular, a complexity significantly lower than that of the non-multipole version was shown to be achieved. A full FM-BEM based on the proposed acceleration method for the half-space Green's tensor is currently under way.

6.2.3. Domain decomposition methods for time harmonic wave propagation

Participants: Francis Collino, Patrick Joly, Mathieu Lecouvez.

This work is motivated by a collaboration with the CEA-CESTA (B. Stupfel) through the PhD thesis of M. Lecouvez that has started at the beginning of the year.

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 is to use a domain decomposition method in which each layer would contitute a subdomain. More precisely, we want to use a non overlaping iterative domain decomposition method based on the use of Robin type transmission conditions, a subject to which people at Poems gave substantial contributions in the 90's through the works of Collino, Desprès, and Joly.

The novelty of our approach consists in using new transmission conditions using some specific impedance operators in order to improve the convergence properties of the method (with respect to more standard Robin conditions). Provided that such operators have appropriate functional analytic properties, the theory shows that one achieves geometric convergence (in opposition the the slow algebraic convergence obtained with standard methods). These properties prevent the use of local impedance operator, a choice that was commonly done for the quest of optimized transmission conditions (following for instance the works of Gander, Japhet, Nataf). We propose a solution that uses nonlocal integral operators using appropriate Riesz potentials. To overcome the disadvantage of dealing with completely nonlocal operators, we suggest to work with truncated kernels, i.e. with operators of the form (Γ represents one interface)

$$u(x) \quad \longrightarrow \quad \int_\Gamma K\,(\,|x-y|\,)\ \chi\left(\frac{|x-y|}{\lambda}\right)\ u(y)\ d\sigma(y)$$

where $K(|x|)$ is an appropriate singlar kernel (typically $K(|x|) = |x|^{-\gamma}$) and $\chi(\rho)$ an adequate smooth cut-off function. Playing with a few parameters such as the size of the support of χ, we expect to achieve an optimal compromise between the reduction of the number of iterations of the method and the cost of each iteration.

6.2.4. Time harmonic aeroacoustics

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

We are still working on the numerical simulation of the acoustic radiation and scattering in presence of a mean flow. This is the object of the ANR project AEROSON, in collaboration with Florence Millot and Sébastien Pernet at CERFACS, Nolwenn Balin at EADS and Vincent Pagneux at the Laboratoire d'Acoustique de l'Université du Maine. Let us recall that our method combines, a Finite Element resolution of the augmented Galbrun equation and of the coupled vorticity transport equation, and the use of Perfectly Matched Layers (PML) to bound the computational domain. The main recent improvements concern the test of the method in presence of unstable modes.

When determining the aeroacoustics modes propagating in a flow, unstable modes exist for certain types of flows: when an inflection point exists in the velocity profile and when the shear in this point is strong enough. Such modes grow exponentially in space. Up to recently, our numerical simulations have been performed for stable flows. We have tested the behavior of PML in the presence of unstable modes, which usually convert a propagating field in a decaying field. Therefore we do not have a theoretical framework to characterize the behavior of PML in the presence of spatially growing modes but the various conducted numerical tests have shown that our numerical method is still able to select the outgoing solution, even in the presence of instabilities, if the attenuation in the PML is strong enough.

6.2.5. Multiple scattering in a duct

Participant: Jean-François Mercier.

This topis is developed in collaboration with Agnès Maurel (Langevin Institute ESPCI).

The objective of this work, part of the ANR Procomedia, is to develop analytical methods to describe the propagation of acoustic waves in 2D waveguides containing penetrable inclusions. Scatterers of arbitrary shape with a contrast in both density and sound speed are considered. A modal approach is adopted, in which the wave equation is projected onto the transverse modes of the homogeneous guide. For each mode a 1D wave equation is obtained with a source term which characterizes the scatterers and couples modes together. In weak scattering regime (small scatterers or low contrasts or low frequency), the Born approximation is used to solve analytically this family of coupled ODE. This gives an explicit prediction for the scatterered field, in particular the reflection and transmission coefficients are obtained in two cases of interest: periodically or randomly distributed scatterers. In both cases, expressions similar to those in free space (available only for low frequencies) are obtained without frequency limit, thanks to the presence of a shape factor sensitive to the geometry of the scatterers at high frequencies.

Recently the obtained analytical expressions have been exploited to develop a very simple imaging method in a heterogeneous waveguide. Measurements of low-frequency reflection and transmission allow to find the position of the object while the higher frequency measurements give access to the shape and to the physical characteristics of the scatterers. The results are good in the case of low contrast and small scatterers, for which the Born approximation is perfectly valid.

6.2.6. *Localization in perturbed periodic metamaterials*

Participant: Jean-François Mercier.

This topis is developed in collaboration with Agnès Maurel, Abdelwaheb Ourir (Langevin Institute ESPCI) and Vincent Pagneux (LAUM).

The aim of this work, part of the ANR Procomedia, is to study the propagation of electromagnetic waves through 1D perturbed periodic media. The attenuation length in a medium consisting of alternating materials of optical indices $n_1 > 0$ and $n_2 < 0$ (metamaterials) is determined. When such medium is randomly disturbed, the localization properties differ significantly from those obtained in a classical disturbed medium: in the homogeneous case $n_1 = n_2$, a random perturbation of the indices induces the Anderson localization with a strong field attenuation. In contrast, in the case $n_1 = -n_2$, it was recently shown that the introduction of disorder on the permittivities ϵ_1 and ϵ_2 gave rise to an "anomaly", the suppression of the Anderson localization. This anomaly results in a significant increase of the attenuation length l_N for large sample sizes N.

We have made two improvements to existing works: simple analytical expressions of the attenuation length have been determined, valid over a wide range of frequencies and of number of layers. In addition we considered realistic metamaterials by taking into account disorder in both the permittivity and the permeability μ. When only the permeability is disturbed (or only the permittivity), our analytical expression can explain the transition to the abnormal behavior when the number of layers increases. Furthermore we show that the anomaly is strongly affected when disturbances in permeability and permittivity are jointly considered: the coupling of the two effects is capable of reseting the usual localization.

6.2.7. *Modeling of meta-materials in electromagnetism*

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

This topis is developed in collaboration with Eric Chung (Chinese Univ. of Hong Kong) and Xavier Claeys (Paris VI).

Meta-materials can be seen as particular media whose dielectric and/or magnetic constant are negative, at least for a certain range of frequencies. This type of behavior can be obtained, for instance, with particular periodic structures. Of special interest is the transmission of an electromagnetic wave between two media with opposite sign dielectric and/or magnetic constants. As a matter of fact, applied mathematicians have to address challenging issues, both from the theoretical and the discretization points of view. The year 2012 saw the completion of Lucas Chesnel PhD thesis. We present below the main results obtained these last three years. The first topic we considered a few years ago was: when is the (simplified) scalar model well-posed in the classical H^1 framework? It turned out this issue could be solved with the help of the so-called T-coercivity framework. While numerically, we proved that the (simplified) scalar model could be solved efficiently by the most “naive” discretization, still using T-coercivity. Recently, we have been able to provide

sharp conditions for the T-coercivity to hold in general 2D and 3D geometries, which involve explicit estimates in simplified geometries together with localization arguments. We then analyzed the discretization of the scalar problem with a classical, H^1 conforming, finite element method, and proved the convergence under the same sharp conditions. We also showed that the problem can be solved with the help of a Discontinuous Galerkin discretization, which allows one to approximate both the field and its gradient (with E. Chung).
As a second topic, we investigated the case of a 2D corner which can be ill-posed (in the classical H^1 framework). Using the Mellin transform, we showed that a radiation condition at the corner has to be imposed to restore well-posedness (with X. Claeys). Indeed there exists a wave which takes an infinite time to reach the corner: this “black hole” phenomenon is observed in other situations (elastic wedges for example). We proposed a numerical approach to approximate the solution which consists in adding some PMLs in the neighbourhood of the corner.
Last, we studied the transmission problem in a purely 3D electromagnetic setting from a theoretical point of view. We proved that the Maxwell problem is well-posed if and only if the two associated scalar problems (with Dirichlet and Neumann boundary conditions) are well-posed. Of course, these scalar problems involves sign-changing coefficients but they can be studied using simple scalar `T`-coercivity approach.
C. Carvalho started her PhD thesis this fall in the continuation of these works.

6.2.8. Numerical MicroLocal Analysis

Participants: Jean-David Benamou, Francis Collino, Simon Marmorat.

Numerical microlocal analysis of harmonic wavefields is based on a family of linear filters using Bessel functions and applied to wave data collected on a circle of fixed radius r_0 around the observation point x_0 where we want to estimate the Geometric Optics/ High Frequency components. The data can easily be reconstructed from more conventional line array or grid geometry. The output is an angular function presenting picks of amplitudes in the direction angles of rays.

The original `NMLA` algorithm relied on a local plane wave assumption for the data. For arbitrary waves, it meant linearization errors and accuracy limitations. Also, only the directions of the (multiple) rays are recovered but the traveltime and amplitudes are not reliably computed. We recently introduced a new "impedant" observable which allows to prove a stability theorem. Numerical results confirm that the new `NMLA` filter is robust to random and correlated noise.

Using asymptotic expansion on `NMLA` filtered point sources data, we designed a correction method for the angle which also estimates the wavefront curvature. It can be used to correct the linearization errors mentioned above and provides a second order correction in the Taylor approximation of the traveltime.

The parameters of the method (size of observation circle, discretization) are automatically optimized and a posteriori quantitative error on angles and curvature are available. Numerical studies validate the stability result and confirm the superior accuracy of the curvature corrected `NMLA` version over image processing methods.

When some bandwith is available we can also compute the traveltime. The amplitude remains polluted by phase errors. Its determination is still open.

6.3. Absorbing boundary conditions and absorbing layers

6.3.1. Evolution problems in perturbed infinite periodic media

Participant: Sonia Fliss.

For parabolic problems set in locally perturbed periodic media, we have developed an approach to determine the time-domain DtN operator. The principle is to apply the Laplace Transform in time to the equation and use the construction of the DtN operator for stationary equations. The main difficulty is the computation of the inverse of the Laplace Transform, more precisely to understand how to deal with the unbounded interval of integration and the choice of the discretization of the laplace variable. To deal with the first difficulty for waveguide problem, we have studied the asymptotic behavior of the DtN operator in the laplace domain when the laplace variable tends to $p_0 \pm \infty$. To deal with the second difficulty, we have used the Z-Transformation and its properties. The numerical study is still in progress. This work enters in the framework of the ANR PRoject MicroWave (Sonia Fliss is an external collaborator), in collaboration with Karim Ramdani (Institut Elie Cartan de Nancy, UMR CNRS 7502), Christophe Besse and Ingrid Violet (Laboratoire Paul Painlevé, UMR CNRS 8524).

6.3.2. New transparent boundary conditions for time harmonic acoustic problem in anisotropic media

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

This topis is developed in collaboration with Vahan Baronian (CEA). Many industrial applications require to check the quality of structures such as plates, for instance in aircraft design. A common way to inspect structures is to propagate ultrasonic waves and detect from the experimental results the presence or not of a defect or a crack. However, in aeronautics, structures are often complex media like anisotropic elastic plates for which the interpretation of this results is complicated. Therefore, efficient and accurate numerical methods of simulation are required. In our work, we want to study the diffraction of a time harmonic wave by a bounded defect in an anisotropic elastic media. In order to study the diffraction properties of the defect, we consider it in as infinite. Since the defect has an arbitrary geometry, we want to use a finite element method in a box that surround the defect. On the boundary of this artificial box, we need to find transparent conditions to simulate an infinite domain.

- We first have considered waveguides. The transparent boundary conditions are often written by using the so-called Dirichlet-to-Neumann maps which can be expressed thanks to a modal decomposition. However, classical iterative method does not converge necessarily. In this work, we introduce a new Dirichlet-to-Neumann operator which links the trace of the solution on a section of the waveguide to the normal trace on a different one. This operator can also be expressed analytically via a modal decomposition. Its main advantage is that, because of the overlapping, it becomes compact and this is exactly why we think an iterative resolution has more chance to converge. Other advantages will appear with the elasticity application. Indeed, in the formulation of the transparent boundary condition without overlapping, appears a lagrange multiplier which makes the resolution more costly. This additional unknown will be avoided with an overlap. For now, the theory is done for the scalar acoustic waveguide and the method has been implemented in the Melina code for the acoustic and the elastic case. The redaction of an article is in progress.

  item We then have studied scattering problem in locally perturbed anisotropic plate. The classical methods to derive transparent boundary conditions for acoustic isotropic media are based on the Green function (boundary integral formulation) or Fourier series (to determine DtN operator set on an artificial circle boundary). However, they cannot be extended for anisotropic elastic problems. Using a constructive method to determine transparent boundary conditions for periodic media developped in the laboratory, we were able to propose new exact boundary conditions which are adapted to anisotropic media and for which iterative method could converge rapidly. The numerical study is in progress for acoustic isotropic problem.

6.4. Waveguides, resonances, and scattering theory

6.4.1. Localized modes in periodic waveguides

Participants: Anne-Sophie Bonnet-Ben Dhia, Bérangère Delourme, Sonia Fliss, Sergei Nazarov, Elizaveta Vasilevskaia.

The general objective is the study of localized modes in locally perturbed periodic media. We investigate the existence theory of such modes as well as their numerical computations. We can distinguish two types of problems.

Numerical computation of guided modes in periodic media with line defects. We are interested in the propagation of guided modes that propagate in the direction of the line defect (which is parallel to one of the periodicity directions of the unperturbed medium) and decrease exponentially in the transverse directions. We aim at computing these modes and their dispersion relation. Last year, we developed a method based on the use of the DtN approach introduced in the PhD thesis of S. Fliss and the resolution of "operator pencil" eigenvalue problems. This year, in collaboration with Kersten Schmidt, we have made a numerical comparison of this new method with the more standard supercell method.

Existence of localized modes in closed periodic waveguides. We consider a propagation medium which is infinite and periodic in one space dimension and bounded in the transverse ones. We investigate the question of the influence of a local defect on the existence of localized modes. Once again this reduces to a selfadjoint eigenvalue problem in an unbounded domain.

The first problem that we studied is in the framework of the PostDoc of Bérangère Delourme. We have considered general locally perturbed periodic media for which we focus on determining sufficient conditions on the periodic media or the local defect so that it exists at least one eigenvalue below the essential spectrum of the underlying perfectly periodic operator. These sufficient conditions are based on Min-Max theory and an appropriate choice of test functions. We were able to validate these existence conditions thanks to the numerical method based on the use of DtN operators. For situations where the periodic "reference medium" is closed to a simple "limit medium" fo which all calculations can be made by hand, we show that these conditions could be really simple and explicit using perturbation theory and asymptotic expansions of the eigenvalues. We are investigating now the extension of this approach to sufficient conditions for existence of guided modes inside the essential spectrum.
The second case, that is investigated in the framework of the PhD thesis of E. Valisevskaia, is the case where the propagation medium is a thin structure (the thinness being characterized by the parameter ε) whose limit is a periodic graph. This is for instance the case of a symmetric ladder as illustrated by figure . If Neumann boundary conditions are considered, it is well known (see in particular the works by Exner, Kuchment) the the limit model when εtends to is the Helmholtz equation on the graph (1D Helmholtz equations on each branch competed by continuity and Kirchoff transimission conditions at each node) . For this limit problem, the underlying operator does not present any spectral gaps but can be written, due to the symmetry of the problem, as the sum of two operators, each of which having an infinity of spectral gaps. This allows us to look for eigenvalues in these spectral gaps, induced by symmetric and localized perturbations of the limit graph model. This can de done for instance by modifying (symetrically) the Kirchoff conditions on two symmetric nodes of the graph. In the limit process mentionned above, this would correspond to modifying the width of the rung that joins these two points in the original problem. First existence results have been obtained in this direction. In a further step, one can expect, by asymptotic analysis, to get corresponding existence results for the original problem, at least for ε small enough.

6.4.2. A new approach for the numerical computation of non linear modes of vibrating systems

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

A collaboration with Cyril Touzé and François Blanc (Unité de Mécanique, ENSTA). The simulation of vibrations of large amplitude of thin plates or shells requires the expensive solution of a non-linear finite element model. The main objective of the proposed study is to develop a reliable numerical method which reduces drastically the number of degrees of freedom. The main idea is the use of the so-called non-linear modes to project the dynamics on invariant subspaces, in order to generate accurate reduced-order models. Cyril Touzé from the Unité de Mécanique of ENSTA has derived an asymptotic method of calculation of the non-linear modes for both conservative and damped systems. But the asymptotically computed solution remains accurate only for moderate amplitudes. This motivates the present study which consists in developing a numerical method for the computation of the non-linear modes, without any asymptotic assumption. This is the object of a collaboration with Cyril Touzé, and new results have been obtained during the post-doc of François Blanc in the Unité de Mécanique of ENSTA. The partial differential equations defining the invariant manifold of the non-linear mode are seen as a vectorial transport problem : the variables are the amplitude and the phase (a, φ) where the phase φ plays the role of the time. In the case of conservative systems, a finite difference scheme is used and an iterative algorithm is written, to take into account the 2π-periodicity in φ which is seen as a constraint. An adjoint state approach has been introduced to evaluate the gradient of the coast function. The method has been validated in a simple example with two degrees of freedom. Good agreement with an alternative method, the continuation of periodic solutions method, has been found. Currently the method is extended to the case of damped systems. The main difficulty is that, due to a change of variables, the 2π-periodicity does not hold anymore and new constraints more complicated to implement must be considered.

6.4.3. Harmonic wave propagation in locally perturbed periodic waveguide

Participants: Sonia Fliss, Patrick Joly.

We work on the expression and the asymptotic behaviour of the Green function for time harmonic wave equation in two-dimensional periodic waveguide. This enables us to define a radiation condition and show well-posedness of the Helmholtz equation set in a periodic waveguide. The redaction of an article is ongoing. This analysis is one of the main tool to solve inverse problems in locally perturbed periodic waveguide (see section 6.6.1) when the data are far field measurements of scattering problems.
One challenging perspective of this work is to extend these results to periodic problems in free space.

6.4.4. Finite element approximation of modes of elastic waveguides immersed in an infinite fluid

Participants: Anne-Sophie Bonnet-Ben Dhia, Cédric Doucet, Christophe hazard.

This work is developped in collaboration with Vahan Baronian (CEA). We are developping numerical tools to simulate ultrasonic non-destructive testing in elastic waveguides. This particular topic aims at finding an efficient way of coupling semi-analytical finite element methods and perfectly matched layers (PMLs) to compute modes of elastic waveguides embedded in an infinite fluid.
During our numerical investigations, we noticed that the semi-analytical mixed finite element formulation proposed in the PhD thesis of V. Baronian may lead to the computation of spurious modes. We overcame this problem in the following way: instead of approximating components of stress tensors by means of first-order finite elements of class $\mathcal{C}^0$, we decided to use zeroth-order discontinuous ones. This simple modification seems not only to stabilize the discretization step, but also to approximate modes more accurately in comparison with the classical semi-analytical finite element formulation. Last but not least, we observed a meaningful improvement of the approximation of the continuous spectrum of stretched operators related to PMLs. Besides, previous results (in the PhD thesis of B. Goursaud) about the best way of designing PMLs to simulate wave propagation in open acoustic waveguides have been confirmed by our numerical experiments on immersed elastic structures.
Further investigations need to be carried out to explain these phenomena. Especially, a theoretical analysis still remains to be done.

6.5. Asymptotic methods and approximate models

6.5.1. Effective boundary conditions for thin periodic coatings

Participants: Mathieu Chamaillard, Patrick Joly.

This topic is the object of a collaboration with Houssem Haddar. We are interested in the construction of "equivalent" boundary condition for the diffraction of waves by an obstacle with smooth boundary Γ covered with a thin coating of width δ whose physical characteristics vary "periodically along Γ with a period proportional to the small parameter δ. For a general boundary Γ, the notion of periodicity is ambiguous: we have chosen to define the coating as the image, or the deformation, by a smooth mapping of a flat layer of width delta (the reference configuration) that preserves the normals, which appears consistent with a manufactoring process. The electromagnetic parameters in the coating are then defined as the images through Φ_Γ of periodic functions in the reference configuration.

We have first considered the case of the scalar wave equation. Using an asymptotic analysis in δ, which combines homogenization and matched asymptotic expansions, we have been able to establish a second order boundary condition of the form

$$\partial_\nu u + \left(\delta\, B_\Gamma^1 + \delta^2\, B_\Gamma^2\right) u = 0$$

where B_Γ^1 and B_Γ^2 are second order tangential differential operators along Γ whose coefficients depend on both the geometrical characteristics of Γ (through the curvature tensor) and the material properties of the coating, through the resolution of particular cell problems in the flat reference configuration. When the coating is homogeneous, we have checked that one recovers the well known second order thin layer condition. This new condition is expected to provide $O(\delta^3)$ accuracy. Its implementation and its rigorous analysis (error estimates) are ongoing.

6.5.2. Thin Layers in Isotropic Elastodynamics

Participants: Marc Bonnet, Aliénor Burel, Patrick Joly.

This research is developed in the framework the numerical modeling of non-destructive testing experiments using ultrasonic waves. Most realistis propagation media involves thin layers of resin (typically for gluing together different homogeneous media), which are, until now, difficult to take into account numerically, the principal issue being the very small space step needed for meshing such a thin layer. An idea to get rid of this complication is to use asymptotic analysis in order to establish effective transmission conditions. We have studied the simple model problem in two dimensions, with an infinite flat layer of thickness ε. Using a formal approach based on a scaling inside the layer and an power series expansion in ε solution as a polynomial in ε, we have established first and second order conditions. Energy techniques parmit to guaranty the stability of our approximation.

6.5.3. Homogenization and metamaterials

Participants: Sonia Fliss, Patrick Joly, Valentin Vinoles.

This topic is developped in collaboration with Xavier Claeys (LJLL, Paris VI).
The mathematical modeling of electromagnetic metamaterials and the homogenization theory are intimately related because metamaterials are precisely constructed by a periodic assembly of small microstructures involving dielectric materials presenting a high contrast with respect to a reference medium. As a consequence, each microstructure behaves as a resonator which induces surprising properties to the effective or homogenized material such as negative permittivity and / or permeability at certain frequencies. The relevant theoretical approach to this question is the non standard (or high contrast) homogenization theory developed in particular in France by G. Bouchitté.

In the framework of the ANR Metamath, we wish to deepen this question by looking carefully at the treatment of boundaries and interfaces that are generally poorly taken into account by the first order homogenization. This is developed in collaboration with X. Claeys (Paris VI).

This question is already relevant for standard homogenization for which taking into account the presence of a boundary induces a loss of accuracy due to the inadequation of the standard homogenization approach to take into account the boundary layers induced by the boundary. Our objective is to construct approximate effective boundary conditions that would restore the desired accuracy.

With the PhD thesis of V. Vinoles, we aim at extending the previous approach to the treatment of metamaterials via high contrast homogenization. In particular, we intend to treat the challenging question of interfaces between metamaterials and standard materials (see also sections).

6.5.4. *Asymptotic analysis and negative materials*

Participants: Lucas Chesnel, Sergei Nazarov.

This topic is developped in collaboration with Xavier Claeys (LJLL, Paris VI) and S.A. Nazarov (IPME RAS, St Petersburg, Russia).
One of the applications of negative materials (metals at optical frequencies or negative metamaterials) is the construction of subwavelength cavities. In this kind of application, the idea is to use the following result: an inclusion of a negative material in a positive material changes radically the spectrum of the Maxwell's operators. We demonstrated this result for the scalar operator in a configuration where a positive material contains a small negative inclusion whose size tends to zero. As a second topic, we proved an instability result for a configuration where the interface between the positive and the negative material has a rounded corner. It appears that the solution depends critically on the value of the rounding parameter and does not converge when the rounded corner tends to the actual corner. We also studied the spectrum of the scalar operator in this configuration. This spectrum does not converge but seems (for the moment, the proof is not complete) to oscillate like $\ln \delta$ where $\delta \to 0$ is the rounding parameter.

6.5.5. *Modelling of non-homogeneous lossy coaxial cable for time domain simulation.*

Participants: Geoffrey Beck, Sébastien Imperiale, Patrick Joly, Martina Novelinkova.

This topic, initiated at the end of the PhD thesis of S. Imperiale, has been the subject of the internship of M. Novelinkova and is the subject of the PhD thesis of G. Bech which started in October.

We investigate the question of the electromagnetic propagation in thin electric cables from a mathematical point of view via an asymptotic analysis with respect to the (small) transverse dimension of the cable: as it has been done in the past in mechanics for the beam theory from 3D elasticity, we use such an approach for deriving simplified effective 1D models from 3D Maxwell's equations. Doing so, we have been able to derive a generalized telegraphist's equation, a 1D wave equation with additional time convolution terms that results from the conjugated effect of electromagnetic losses and heterogeneity of the cross section. This new model has been fully justified through error estimates. We are currently working on a higher order generalized telegraphist's equation that would include dispersive effects through nonlocal capacity and inductance operators.

From the pratical point of view, a code that computes the coefficients (including the convolution kernel) of the effective model and solves the generalized telegraphist's equation has been implemented. It has been exploited to measure the presence of localized defects on the propagation of electromagnetic waves. This application has been motivated by the ANR project SODDA, in collaboration with CEA-LETI, about the non destructive trsting of networks of electric cables (a subject that we are investigating in collaboration with M. Sorine from Inria Rocquencourt).

6.5.6. *Elastic wave propagation in strongly heterogeneous media*

Participants: Patrick Joly, Simon Marmorat.

This subject enters our long term collaboration with CEA-LIST on the development on numerical methods for time-domain non destructive testing experiments using ultra-sounds. This is also the subject of the PhD thesis of Simon Marmorat. Our objective is to develop an efficient numerical approach for the propagation of elastic waves in a medium which is made of many small inclusions / heterogeneities embedded in a smooth (or piecewise smooth) background medium, without any particular assumption (such as periodicity) on the spatial distribution of these heterogeneities. Our idea is to exploit the smallness of the inclusions (with respect to the wavelength in the background medium) to derive a simplified approximate model in which each inclusion would be described by very few parameters (functions of time) coupled to the displacement field in background medium for which we could use a computational mesh that ignores the presence of the heterogeneities. For deriving such a model. we intend to use and adapt the asymptotic methods previously developed at Poems (such as matched asymptotic expansions).

6.5.7. Multiple scattering by small scatterers

Participants: Maxence Cassier, Christophe Hazard.

We consider the scattering of an acoustic time-harmonic wave by an arbitrary number of sound-soft obstacles located in a homogeneous medium. When the size of the obstacles is small compared with the wavelength, the numerical simulation of such a problem by classical methods (e.g., integral equation techniques or methods based on a Dirichlet-to Neumann map) can become highly time-consuming, particularly when the number of scatterers is large. In this case, the use of an asymptotic model may reduce considerably the numerical cost. Such a model was introduced by Foldy and Lax in the middle of the last century to study multiple isotropic scattering in a medium which contains randomly distributed small scatterers. Their asymptotic model is based on the fact that the scattered wave can be approximated by a wave emitted by point sources placed at the centers of the scatterers; the amplitudes of the sources are calculated by solving a linear system which represents the interactions between the scatterers. Nowadays, the FoldyñLax model is still used in numerous physical and numerical applications to approximate the scattered wave in a deterministic media. But to the best of our knowledge, there was no mathematical justification of this asymptotic model. We have proposed such a justification which provides local error estimates for the two-dimensional problem in the case of circular obstacles. An article on this subject has been accepted and will be published in Wave Motion in January 2013.

6.6. Imaging and inverse problems

6.6.1. Sampling methods in waveguides

Participants: Laurent Bourgeois, Anne-Claire Egloffe, Sonia Fliss, Mathieu Guenel, Eric Lunéville.

First, we have adapted the modal formulation of sampling methods (Linear Sampling Method and Factorization Method) to the case of a periodic waveguide in the acoustic case. This study is based on the analysis of the far field of scattering solutions in cylindrical waveguides, in particular for the fundamental solution, which enables us to obtain a far field formulation of sampling methods, and then a modal formulation of such methods. The aim of the inverse problem is to retrieve a defect from the scattered fields which correspond to the incident fields formed by the Floquet modes. The corresponding numerical implementation was the subject of the Master internship of Mathieu Guenel who obtained some first promising results.
Secondly, going back to the homogeneous waveguide in the acoustic case, we have started a study of the sampling methods in the time domain. This will be the subject of Anne-Claire Egloffe's post-doc. The aim is to use the modal formulation of the sampling methods at all frequencies and recompose the best possible image of the defect.

6.6.2. The exterior approach to retrieve obstacles

Participant: Laurent Bourgeois.

This theme is a collaboration with Jérémi Dardé from IMT (Toulouse).

We have adapted the exterior approach developped for the Laplace equation to the Stokes system. The aim is to find a fixed Dirichlet obstacle in a fluid which is governed by the Stokes system with the help of boundary measurements. The exterior approach consists in defining a decreasing sequence of domains that converge in some sense to the obstacle. More precisely, such iterative approach is based on a combination of a quasi-reversibility method to update the solution of the ill-posed Cauchy problem outside the obstacle obtained at previous iteration and of a level set method to update the obstacle with the help of the solution obtained at previous iteration. In particular, we have introduced two different mixed formulations of quasi-reversibility for the ill-posed Stokes systems in order to use standard Lagrange finite elements.

6.6.3. Inverse scattering with generalized impedance boundary conditions

Participants: Laurent Bourgeois, Mathieu Chamaillard, Nicolas Chaulet.

This work is a collaboration between POEMS and DEFI projects (more precisely Houssem Haddar) and constitutes the subject of the PhD thesis of N. Chaulet, which was defended on the 27/11/2012. We are concerned with the identification of some obstacle and some Generalized Impedance Boundary Conditions (GIBC) on the boundary of such obstacle from far field measurements generated by the scattering of harmonic incident waves. The GIBCs are approximate models for thin coatings, corrugated surfaces, rough surfaces or imperfectly conducting media.

During this last year, we complemented our previous work in two directions. First, we justified the use of the Factorization method to solve the inverse obstacle problem in the presence of GIBCs. This method gives a uniqueness proof as well as a fast algorithm to reconstruct the obstacle from the knowledge of the far field produced by incident plane waves for all the directions of incidence at a given frequency. We also provided some numerical reconstructions of obstacles for several impedance operators.

Meanwhile, we studied the application of non linear optimization techniques to solve the inverse problem for the $3D$ Maxwell's equations. The main advantage of this type of method is that they can be applied with much less data than the Factorization method. Nevertheless, we had to compute the partial derivatives of the electromagnetic field with respect to the parameters we want to reconstruct. In our case, these parameters are the coefficients that define the impedance operator and the shape of the obstacle. We characterized these derivatives in the case where the GIBC is defined by a second order surface operator. The applicability of such methods has been illustrated by some numerical experiments in dimension 3 in which we reconstructed the shape of the scatterer as well as the coefficients that characterize the impedance operator. As demonstrated in the two dimensional case, we think that the GIBCs could be efficiently used to identify the shape of coated objects as well as the parameters of the coating in the $3D$ Maxwell case.

6.6.4. Linear sampling methods in the time domain

Participant: Simon Marmorat.

This work is developed in collaboration with H. Haddar (DEFI, Inria Saclay) and A. Lechleiter (Bremen University). We are concerned with the inverse problem of reconstructing obstacles from the knowledge of scattered acoustic waves in the time domain. We tackle this problem using a linear sampling method that directly acts on time domain data: this imaging technique yields a picture of the scatterer by solving a linear operator equation involving the measured data for many right-hand sides given by singular solutions to the wave equation. We have illustrated the method on numerical examples and have shown a good behaviour with respect to aperture (the quality of reconstruction is better than in the frequency case in the case of limited aperture) and the ability of simultaneously reconstructing obstacles with different boundary conditions among the Dirichlet, Neumann and Robin-Fourier ones.

6.6.5. Space-time focusing on unknown scatterers

Participants: Maxence Cassier, Patrick Joly, Christophe Hazard.

This topic concerns the studies started two years ago about time-reversal in the context of Maxence Cassier's thesis. The main question is to generate a time-dependent wave that focuses on one given scatterer not only in space, but also in time. Our recent works concern two items. On one hand, we have proposed a way to construct such a focusing wave which does not require an a priori knowledge of the location of the obstacle. This wave is represented by a suitable superposition of the eigenvectors of the so-called time-reversal operator in the frequency domain. Numerical results show the focusing properties of such a wave. On the other hand, we try to understand how to translate the physical idea of ìfocusingî into mathematical terms. We proposed and and implemented energy criterion which can be used in numerical experiments in order to evaluate the quality of the focus.

6.6.6. Asymptotic analysis of the interior transmission eigenvalues related to coated obstacles

Participant: Nicolas Chaulet.

This work is a collaboration with Fioralba Cakoni from the University of Delaware (USA) and Houssem Haddar from the DEFI project. The interior transmission eigenvalues play an important role in the area of inverse scattering problems. These eigenvalues can actually be determined by multi-static far field data. Thus, they could be used for non destructive testing. We focused on the case where the obstacle is a perfectly conducting body coated by some thin dielectric material. We derived and justified the asymptotic expansion of the first interior transmission eigenvalue with respect to the thickness of the coating for the TM electromagnetic polarization. This expansion provided interesting qualitative information about the behavior of these eigenvalues and also gave an explicit formula to compute the thickness of the coating.

6.6.7. Interior transmission problem

Participants: Anne-Sophie Bonnet-Ben Dhia, Lucas Chesnel, Jérémi Firozaly.

This work is a collaboration with F. Cakoni from the University of Delaware (U.S.) and H. Haddar from the DEFI project at Inria Saclay. The interior transmission problem plays an important role in the inverse scattering theory for inhomogeneous media. In particular, it arises when one is interested in the reconstruction of an inclusion embedded in a background medium from multi-static measurements of diffracted fields at a given frequency. Physically, it is important to prove that, for a given frequency, there are no waves which do not scatter. Mathematically, this last property boils down to state that the frequency is not a transmission eigenvalue, that is, an eigenvalue of the interior transmission problem. An important issue is to prove that transmission eigenvalues form at most a discrete set with infinity as the only accumulation point. This is not straightforward because the operator associated with this problem exhibits a sign changing in its principal part and its study is not standard. Using the T-coercivity approach, we proved the discreteness under relatively weak assumptions both for the scalar and Maxwell cases. In particular, the simple technique we proposed allows to treat cases, which were not covered by existing methods, where the difference between the inclusion index and the background index changes sign. Now, we are trying to understand the fundamental links which exist between this problem and the transmission problem between a positive and a negative material. In some configurations, the study of the interior transmission problems leads to consider the operator $\Delta(\sigma\Delta\cdot) : H_0^2(\Omega) \to H^{-2}(\Omega)$ where Ω is the domain and σ is a coefficient which changes sign on Ω. During the internship of Jérémy Firozaly, we proved that this operator exhibits properties very different from the operator $\text{div}(\sigma\nabla\cdot) : H_0^1(\Omega) \to H^{-1}(\Omega)$.

6.6.8. Flaw identification using elastodynamic topological derivative

Participants: Marc Bonnet, Rémi Cornaggia.

In collaboration with Cédric Bellis (Columbia Univ. USA), Bojan Guzina (Univ. of Minnesota, USA).
The concept of topological derivative (TD) quantifies the perturbation induced to a given cost functional by the nucleation of an infinitesimal flaw in a reference defect-free body, and may serve as a flaw indicator function. In this work, the TD is derived for three-dimensional crack identification exploiting over-determined transient elastodynamic boundary data. This entails in particular the derivation of the relevant polarization tensor, here given for infinitesimal trial cracks in homogeneous or bi-material elastic bodies. Simple and efficient adjoint-state based formulations are used for computational efficiency, allowing to compute the TD field for arbitrarily

shaped elastic solids. The latter is then used as an indicator function for the spatial location of the sought crack(s). Current investigations focus on justifying the heuristic underpinning TD-based identification, which consists in deeming regions where the TD is most negative as the likeliest locations of actual flaws and on formulating higher-order topological expansions in the elastodynamic case.

6.6.9. Topological derivative in anisotropic elasticity

Participant: Marc Bonnet.

In collaboration with Gabriel Delgado (CMAP, Ecole Polytechnique).
Following up on previous work on the topological derivative (TD) of displacement-based cost functionals in anisotropic elasticity, a TD formula has been derived for general cost functionals that involve strains (or displacement gradients) rather than displacements. The small-inclusion asymptotics of such cost functionals are quite different than in the previous case, due to the fact that the strain perturbation inside an elastic inclusion remains finite no matter how small the inclusion size. Cost functionals of practical interest having this format include von Mises equivalent stress (often used in plasticity or failure criteria) and energy-norm error functionals for coefficient-identification inverse problems.

6.6.10. Energy functionals for elastic medium reconstruction using transient data

Participant: Marc Bonnet.

In collaboration with Wilkins Aquino (Cornell Univ., USA).
Energy-based misfit cost functionals, known in mechanics as error in constitutive relation (ECR) functionals, are known since a long time to be well suited to (electrostatic, elastic,...) medium reconstruction. In this ongoing work, a transient elastodynamic version of this methodology is developed, with emphasis on its applicability to large time-domain finite element modeling of the forward problem. The formulation involves coupled transient forward and adjoint solutions, a fact which greatly hinders large-scale computations. A computational approach combining an iterative treatment of the coupled problem and the adjoint to the discrete Newmark time-stepping scheme is found to perform well on large FE models, making the time-domain ECR functional a worthwhile tool for medium identification.

6.7. Other topics

6.7.1. Fast non-overlapping Schwarz domain decomposition methods for the neutron diffusion equation

Participant: Patrick Ciarlet.

A collaboration with Erell Jamelot (CEA Saclay/DEN).
Investigating numerically the steady state of a nuclear core reactor can be very expensive, in terms of memory storage and computational time. In order to address both requirements, one can use a domain decomposition method, which is then implemented on a parallel computer.
We model the problem using a mixed approach, which involves a scalar flux and a vector current. The equivalent variational formulation is then discretized with the help of Raviart-Thomas-Nédélec finite elements. The domain decomposition method is based on the Schwarz iterative algorithm with Robin interface conditions to handle communications. This method is analyzed from the continuous to the discrete point of views: well-posedness, convergence of the finite element method, optimality of the parameter appearing in the Robin interface condition and algorithms. Numerical experiments carried out on realistic 3D configurations using the APOLLO3©code (of CEA/DEN) show the parallel efficiency of the algorithm.

7. Bilateral Contracts and Grants with Industry

7.1. Contract POEMS-CEA-LIST-2

Participant: Anne-Sophie Bonnet-Ben Dhia.

Start : 09/01/2010, End : 07/31/2013. Administrator : ENSTA.
This contract is about the scattering of elastic waves by a stiffener in an anisotropic plate.

7.2. Contract POEMS-CEA-LIST-3

Participants: Laurent Bourgeois, Eric Lunéville.

Start : 10/01/2011, End : 09/30/2012. Administrator : ENSTA.
This contract is about the linear sampling methods for elastic waveguides.

7.3. Contract POEMS-CEA-LIST-DIGITEO

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

Start : 10/01/2011, End : 09/30/2014. Administrator : ENSTA.
This contract is about the scattering of elastic waves by a local defects in an anisotropic plate. It consists on the funding of Antoine Tonnoir's Phd.

7.4. Contract POEMS-DGA

Participants: Anne-Sophie Bonnet-Ben Dhia, Bérangère Delourme, Sonia Fliss, Patrick Joly.

Start : 09/01/2011, End : 12/31/2013. Administrator : ENSTA.
This contract is about the waveguide 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.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- ANR project *AEROSON: Simulation numérique du rayonnement sonore dans des géométries complexes en présence d'écoulements réalistes*
  Partners: EADS-IW, CERFACS, Laboratoire d'Acoutique de l'Université du Maine.
  Start : 10/01/2009, End : 02/28/2013. Administrator : CNRS. Coordinator : Jean-François Mercier.
- 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, DMIA-ISAE.
  Start : 12/01/2011, End : 11/30/2015. 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

8.1.2. Competitivity Clusters

- GDR Ultrasons: this GDR, which regroups more than regroup 15 academic and industrial research laboratories in Acoustics and Applied Mathematics working on nondestructive testing. It has been renoveled this year with the participation of Great Britain.

8.2. European Initiatives

8.2.1. FP7 Projects

8.2.1.1. SIMPOSIUM

Title: Simulation Platform for Non Destructive Evaluation of Structures and Materials

Type: COOPERATION (ICT)

Defi: PPP FoF: Digital factories: Manufactoring design and product lifecycle manage

Instrument: Integrated Project (IP)

Duration: September 2011 - August 2014

Coordinator: CEA (Pierre Calmont) (France)

Others partners:SERCO LIMITED (UNITED KINGDOM), SIMULAYT LTD (UNITED KINGDOM), SKF SVERIGE AB (SWEDEN), UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II (ITALY), UNIVERSITA DEGLI STUDI DI CASSINO (ITALY), VOLKSWAGEN AG (GERMANY), ARCELORMITTAL MAIZIÈRES RESEARCH SA (FRANCE), EXTENDE (FRANCE), EUROPEAN AERONAUTIC DEFENCE AND SPACE COMPANY EADS FRANCE SAS (FRANCE), IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE (UNITED KINGDOM), SAARSCHMIEDE GMBH FREIFORMSCHMIEDE* (GERMANY), KATHOLIEKE UNIVERSITEIT LEUVEN (BELGIUM), FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V (GERMANY).

See also: http://cordis.europa.eu/projects/rcn/99653_en.html

8.3. International Research Visitors

8.3.1. Visits of International Scientists

- *Sergei Nazarov*, Professor at the University of Saint-Petersbourg.

9. Dissemination

9.1. Scientific Animation

- A. S. Bonnet-Ben Dhia is the Head of the Electromagnetism Group at CERFACS (Toulouse)
- A. S. Bonnet-Ben Dhia is in charge of the relations between l'ENSTA and the Master "Dynamique des Structures et des Systèmes Couplés (Responsible : Etienne Balmes)".
- A. S. Bonnet-Ben Dhia is presidente of the "Conseil scientifique de l'Institut des sciences de l'ingénierie et des systèmes (INSIS-CNRS)".
- M. Bonnet is associate editor of European Journal of Mechanics A/Solids (since Jan. 2008).
- M. Bonnet is associate editor of Engineering Analyses with Boundary Elements (since July 2011).
- M. Bonnet is on the editorial board of *Inverse Problems*.
- M. Bonnet is on the editorial board of *Computational Mechanics*.
- P. Ciarlet is an editor of DEA (Differential Equations and Applications) since July 2008
- P. Ciarlet is an editor of CAMWA (Computers & Mathematics with Applications), since January 2012

- G. Cohen is a scientific expert of ONERA.
- P. Joly is a member of the scientific committee of CEA-DAM.
- P. Joly is a member of the Scientific Committee of the Seminar in Applied Mathematics of College de France (P. L. Lions).
- P. Joly is an editor of the journal Mathematical Modeling and Numerical Analysis.
- P. Joly is a member of the Book Series Scientific Computing of Springer Verlag.
- M. Lenoir is a member of the Commission de Spécialistes of CNAM.
- M. Lenoir is in charge of Master of Modelling and Simulation at INSTN.
- E. Lunéville is the Head of UMA (Unité de Mathématiques Appliquées) at ENSTA.
- The Project organizes the monthly Seminar Poems (Coordinators: A. Burel, N. Chaulet, S. Chaillat, S. Marmorat)

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- Eliane Bécache
  - *Compléments sur la méthode des éléments finis*, ENSTA (2nd year).
  - *Cours sur les PML*, Collège Polytechnique, Paris.
- Anne-Sophie Bonnet-Ben Dhia
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA (1st year).
  - *Propagation dans les guides d'ondes*, ENSTA (3rd year).
  - *Théorie spectrale des opérateurs autoadjoints et applications aux guides optiques*, ENSTA (2nd year).
  - *Propagation des ondes*, Ecole Centrale de Paris (M2).
- Marc Bonnet
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA (1st year).
  - *Problèmes inverses*, Master TACS (ENS Cachan) et DSMSC (Centrale Paris).
  - *Méthodes intégrales*, Master TACS (ENS Cachan).
  - *Equations intégrales et multipôles rapides*, Ecole doctorale MODES (Univ. Paris Est, Marne la Vallée).
- Laurent Bourgeois
  - *Outils élémentaires pour l'analyse des EDP*,ENSTA (1st year).
  - *Fonctions de la variable complexe*,ENSTA (2nd year)
- Aliénor Burel
  - *Probabilités*, IUT d'informatique, Université Paris-Sud XI, Orsay (2nd year).
  - *Analyse*, IUT d'informatique, Université Paris-Sud XI, Orsay (1st year).
- Maxence Cassier
  - *Système dynamique: Stabilité et Commande*, ENSTA (1st year).
  - *Introduction à MATLAB*, ENSTA (1st year).
  - *Fonction de variable complexe*, ENSTA (2nd year)
  - *Tutorat pour élèves en difficulté en mathématiques appliquées*, ENSTA (1st year).
- Stéphanie Chaillat
  - *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA (1st year).
  - *Fonctions de variable complexe*, ENSTA (2nd year)

- Mathieu Chamaillard
  - *Introduction aux équations aux dérivées partielles hyperboliques et à leur discr'etisation*, ENSTA (1st year)
  - *Introduction au Calcul Scientifique*, ENSTA (2nd year)
  - *Tutorat pour élèves en difficulté en mathématiques appliquées*, ENSTA (1st year).
- Nicolas Chaulet
  - *Equations différentielles et introduction à l'automatique*, ENSTA (1st year)
  - *Méthode des éléments finis*, ENSTA (2nd year)
- Patrick Ciarlet
  - *Méthode des éléments finis*, ENSTA, Paris (2nd year)
  - *Compléments sur la méthode des éléments finis*, ENSTA, Paris (2nd year)
  - *Parallélisme et calcul réparti*, ENSTA (3rd year), and Master "Modeling and Simulation" (M2)
  - *Les équations de Maxwell et leur discrétisation*, ENSTA, Paris (3rd year), and Master "Modeling and Simulation" (M2)
- Sonia Fliss
  - *Méthode des éléments finis*, ENSTA, Paris (2nd year)
  - *Programmation scientifique et simulation numérique*, ENSTA, Paris (2nd year)
  - *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA, Paris (1st year).
- Christophe Hazard
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA, Paris (1st year)
  - *Théorie spectrale des opérateurs autoadjoints et applications aux guides optiques*, ENSTA, Paris (2nd year).
- Patrick Joly
  - *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA, Paris (1st year).
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA, Paris (1st year).
- Marc Lenoir
  - *Fonctions de variable complexe*, ENSTA, Paris (2nd year).
  - *Equations intégrales*, ENSTA, Paris (3rd year).
- Eric Lunéville
  - *Introduction au calcul scientifique*, ENSTA, Paris (2nd year)
  - *Programmation scientifique et simulation numérique*, ENSTA, Paris (2nd year)
  - *Propagation dans les guides d'ondes*, , ENSTA, Paris (2rd year)
- Simon Marmorat
  - *Introduction aux équations aux dérivées partielles hyperboliques et à leur discr'etisation*, ENSTA, Paris (1st year)
  - *La méthode des éléments finis*, ENSTA, Paris (2nd year)
- Jean-François Mercier
  - *Outils élémentaires d'analyse pour les EDP*, ENSTA, Paris (1st year).
  - *Fonctions de variable complexe*, ENSTA, Paris (2nd year).
  - *Théorie spectrale des opérateurs autoadjoints et application aux guides optiques*, ENSTA, Paris (2nd year).

- Nicolas Salles
  - *Analyse et séries de Fourier*, Université Paris XI Orsay (L2)
  - *Systèmes Linéaires (Matlab)*, Université Paris XI Orsay (L3)
  - *Calcul scientifique*, Université Paris XI Orsay (L3)

9.2.2. Supervision

HdR : Laurent Bourgeois, "Sur quelques problèmes inverses gouvernés par des équations aux dérivées partielles elliptiques", Université Pierre et Marie Curie, Paris 6, 3 Février 2012

PhD : Juliette Chabassier , "Modeling and numerical simulation of a grand piano", Ecole Polytechnique, 12 Mars 2012, Patrick Joly

PhD : , Nicolas Chaulet, "Modèles d'impédance généralisée en diffraction inverse", Ecole Polytechnique, 27 Novembre 2012, Laurent Bourgeois

PhD : , Lucas Chesnel, "Étude de quelques problèmes de transmission avec changement de signe. Application aux métamatériaux", Ecole Polytechnique, 12 Octobre 2012, Anne-Sophie Bonnet-Ben Dhia, et Patrick Ciarlet

PhD : Sébastien Imperiale, "Modélisation mathématique et numérique de capteurs piézoélectriques", Université Paris IX, 19 Janvier 2012, Gary Cohen et Patrick Joly

PhD in progress : Alienor Burel, "Methodes numériques pour les ondes élastiques en présence d'interfaces minces et de milieux mous", Octobre 2010, Patrick Joly

PhD in progress : Maxence Cassier, "Methodes de retournemet temporel en régime transitoire", Octobre 2010, Christophe Hazard et Patrick Joly

PhD in progress : Matthieu Chamaillard , "Conditions aux limites effectives pour des revêtements minces périodiques", Octobre 2011, 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 : Nicolas Salles, "Stabilisation du calcul des singularités dans les méthodes d'équations intégrales variationnelles", Octobre 2009, Marc Lenoir

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

PhD in progress : Audrey Vigneron , "Formulations intégrales pour la simulation du contrôle non destructif par courants de Foucault", Novembre 2011, Marc Bonnet

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

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

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

PhD in progress : Camille Carvalho, "Guides d'onde plasmonique" , Octobre 2012, Anne-Sophie Bonnet-Ben Dhia, et Patrick Ciarlet

PhD in progress : Valentin Vinoles, "Etude de quelques problèmes mathématiques de la théorie des métamatériaux", Octobre 2012, Sonia Fliss et Patrick Joly

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

9.3. Popularization

- Marc Bonnet
  - *Topological derivative of energy cost functionals - application to flaw identification*, ECCOMAS Conference, Vienne, Austria, September.
  - *An error in constitutive equation approach for transient inverse elastodynamics (with W. Aquino)*, 8th European Solid Mechanics Conference, Graz, Austria, July.
  - *Flaw identification using elastodynamic data and small-defect asymptotics of cost functionals*, 1st Russian-French conference on mathematical geophysics, mathematical modeling in continuum mechanics and inverse problems, Biarritz, June.
- Laurent Bourgeois
  - *Sur une "approche extérieure" pour résoudre le problème inverse de l'obstacle*, Journée "Problèmes inverses", CNAM, June 21th.
  - *An "exterior approach" to solve the inverse obstacle problem for the Stokes system*, Control of Fluid-Structure Systems and Inverse problems, Toulouse, July 25-28th
- Aliénor Burel
  - *Using potentials in elastodynamics : a challenge for FEM*, First Franch-Russian Workshop Conference on Mathematical Geophysics, Continuous Mecanical Modelisation and Inverse Problems, Biarritz, June 18-22th.
  - *Elastic Wave Propagation in Soft Elastic Materials With Thin Layers*, Inria Junior Seminar, Rocquencourt, June 26th.
- Maxence Cassier
  - Recent Advances in Modeling, Analysis and Simulation of Wave Propagation Metz March 29 - March 31st.
  - Wave propagation in complex media and applications, Heraklion, Crete, May 7-11th.
- Stéphanie Chaillat
  - *A New Fast Multipole Method for 3D Elastodynamics based using the Half-Space Fundamental Solutions.* EUROMECH Colloquium 540: Advanced Modelling of Wave Propagation in Solids, Prague, Czech Republic, October 2012.
  - *Fast multipole accelerated boundary integral equation method for 3-D elastodynamic problems in a half-space*, Séminaire du LaMSID, EDF R&D Clamart, France, September 2012.
  - *A New Fast Multipole Method for Elasticity based on the Half-Space Fundamental Solutions*, ECCOMAS 2012, Vienna, Austria, September 2012.
  - *Formulation and Fast Evaluation of the Multipole Expansions of the Elastic Half-Space Fundamental Solutions*, ESMC 2012, Graz, Austria, July 2012.
  - *A new fast multipole formulation for the elastodynamic half-space fundamental solutions*, 4th Workshop BEM on the Saar, Saarbrucken, Germany, May 2012.
- Nicolas Chaulet
  - *Reconstruction of a perfectly conducting obstacle coated with a thin dielectric layer*, PICOF'12, Palaiseau (France), June 4-6th.
  - *A factorization method for support characterization of an obstacle with a generalized impedance boundary condition*, IPMS conference, Antalya (Turkey), May 21-26th.
- Lucas Chesnel
  - *Transmission eigenvalue problems with sign-changing coefficients*, Picof conference, Palaiseau, April.
  - *Time harmonic Maxwell equations with sign changing coefficients*, Around scattering by obstacles and billiards, Aveiro, Portugal, March.

- Sonia Fliss
  - *Wave propagation in locally perturbed periodic infinite media*, Forschungseminar "Amthematische Modelle der Photonik", Berlin, January.
  - *Dirichlet-to-Neumann operators in periodic waveguide : application to the application of trapped modes*. Days on diffraction 2012, May.
  - *A DtN approach for the exact computation of guided modes in a photonic crystal waveguides*, Seminar of CERMICS, Marne La Vallée, June.
  - *On the relevance of effective models of metamaterials near the boundary*, GDR Ultrasons, Paris, December.
- Patrick Joly
  - *Mathematical modelling of non homogeneous coaxial cables for time domain simulation*, Journées Guides d'Ondes, Marseille, 27-28 January 2012
  - *Mathematical modelling of non homogeneous coaxial cables for time domain simulation*, Worshop MOPNET (EPSRC Matrix and Operator Pencil Network), Bath University, England, April 2012
  - *Numerical simulation of a grand piano*, Wave propagation in complex media and applications, Archimedes Center for Modeling, Analysis and Computation (ACMAC), University of Crete, Heraklion, Mai 2012
  - *Asymptotic modelling of electromagnetic wave propagation in co-axial cables*, Workshop on Numerical Solution of Evolution Problems, Heraklion, Crete, Septembre 2012
  - *Mathematical modeling of non-homogeneous lossy co-axial cables for time domain simulation*, Inria Bcam workshop, Biarritz October 2012
- Jean-François Mercier
  - *Time-harmonic acoustic scattering in a complex flow*, Anne-Sophie Bonnet-BenDhia, Jean-François Mercier, Florence Millot, Sébastien Pernet et E. Peynaud, Acoustics 2012, Nantes, avril 2012
  - *Propagation of guided waves through weak penetrable scatterers*, A. Maurel et J.-F. Mercier, Seventh Meeting of the GDR "Wave Propagation in complex media for quantitative and non destructive evaluation", Oléron, May 2012

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] L. BOURGEOIS. *Sur quelques problèmes inverses gouvernés par des équations aux dérivées partielles elliptiques*, Université Paris VI, Feb 2012.

[2] J. CHABASSIER. *Modélisation et simulation numérique d'un piano par modèles physiques*, Ecole Polytechnique X, March 2012, Thèse sous la codirection de Antoine Chaigne, Unité de Mécanique, ENSTA ParisTech, http://hal.inria.fr/pastel-00690351.

[3] N. CHAULET. *Modèles d'impédance généralisée en diffraction inverse*, Ecole Polytechnique X, Nov 2012.

[4] L. CHESNEL. *Étude de quelques problèmes de transmission avec changement de signe. Application aux métamatériaux.*, Ecole Polytechnique X, Oct 2012.

[5] S. IMPERIALE. *Modélisation mathématique et numérique de capteurs piézoélectriques*, Université Paris IX, January 2012.

Articles in International Peer-Reviewed Journals

[6] B. BANERJEE, T. WALSH, W. AQUINO, M. BONNET. *Large Scale Parameter Estimation Problems in Frequency-Domain Elastodynamics Using an Error in Constitutive Equation Functional*, in "Computer Methods in Applied Mechanics and Engineering", 2013, vol. 253, p. 60-72 [*DOI :* 10.1016/J.CMA.2012.08.023], http://hal.inria.fr/hal-00732291.

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[8] C. BELLIS, M. BONNET. *Qualitative identification of cracks using 3D transient elastodynamic topological derivative: formulation and FE implementation*, in "Computer Methods in Applied Mechanics and Engineering", 2013, vol. 253, p. 89-105 [*DOI :* 10.1016/J.CMA.2012.10.006], http://hal.inria.fr/hal-00741515.

[9] J.-D. BENAMOU, F. COLLINO, S. MARMORAT. *Numerical Microlocal analysis of 2-D noisy harmonic plane and circular waves*, in "Asymptotic Analysis", 12 2012.

[10] J.-D. BENAMOU, F. COLLINO, S. MARMORAT. *Source point discovery through high frequency asymptotic time reversal*, in "Journal of Computational Physics", 2012, vol. 231, p. 4643–4661, http://dx.doi.org/10.1016/j.jcp.2012.03.012.

[11] C. BESSE, J. COATLÉVEN, S. FLISS, I. LACROIX-VIOLET, K. RAMDANI. *Transparent boundary conditions for locally perturbed infinite hexagonal periodic media*, in "Communications in Mathematical Sciences", 2013.

[12] F. BLANC, C. TOUZE, J.-F. MERCIER, A.-S. BONNET-BEN DHIA. *On the numerical computation of Nonlinear Normal Modes for reduced-order modelling of conservative vibratory systems*, in "Mechanical Systems and Signal Processing", 2013, à paraitre.

[13] A.-S. BONNET-BEN DHIA, L. CHESNEL, P. CIARLET. *T-coercivity for scalar interface problems between dielectrics and metamaterials*, in "ESAIM: Mathematical Modelling and Numerical Analysis", 2012, vol. 46, p. 1363-1387 [*DOI :* 10.1051/M2AN/2012006], http://hal.inria.fr/hal-00564312.

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[15] A.-S. BONNET-BEN DHIA, J.-F. MERCIER, F. MILLOT, S. PERNET, E. PEYNAUD. *Time-Harmonic Acoustic Scattering in a Complex Flow: a Full Coupling Between Acoustics and Hydrodynamics*, in "Commun. Comput. Phys.", 2 2012, vol. 11(2), p. 555–572.

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[17] L. BOURGEOIS, E. LUNÉVILLE. *On the use of sampling methods to identify cracks in acoustic waveguides*, in "Inverse Problems", 9 2012, vol. 28, 105011 (18pp).

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[24] L. CHESNEL, P. CIARLET. *T-coercivity and continuous Galerkin methods: application to transmission problems with sign changing coefficients*, in "Numer. Math.", 2013.

[25] V. CHIARUTTINI, D. GEOFFROY, V. RIOLO, M. BONNET. *An adaptive algorithm for cohesive zone model and arbitrary crack propagation*, in "European Journal of Computational Mechanics", 2012, vol. 21, p. 208-218 [*DOI :* 10.1080/17797179.2012.744544], http://hal.inria.fr/hal-00752797.

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[27] E. CHUNG, P. CIARLET, T. F. YU. *Convergence and superconvergence of staggered discontinuous Galerkin methods for the three-dimensional Maxwell's equations on Cartesian grids*, in "J. Comput. Phys.", 2013.

[28] P. CIARLET. *T-coercivity: application to the discretization of Helmholtz-like problems*, in "Computers Math. Applic.", 2012, vol. 64, p. 22–34.

[29] J. COATLÉVEN. *Helmholtz equation in periodic media with a line defect*, in "Journal of Computational Physics", 2013.

[30] J. COATLÉVEN. *Transparent boundary conditions for evolution equations in infinite periodic strips*, in "SIAM Journal of Scientific Computing", 2013.

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