Activity Report 2018

Team POEMS-POST

Wave propagation: mathematical analysis and simulation

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
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THEME
Networks and Telecommunications

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Team POEMS-POST

Creation of the Team: 2018 January 01

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2. Overall Objectives

2.1. The topic of waves

The propagation of waves is one of the most common physical phenomena in nature. From the human scale (sounds, vibrations, water waves, telecommunications, radar) to the scales of the universe (electromagnetic waves, gravity waves) and of the atoms (spontaneous or stimulated emission, interferences between particles), the emission and the reception of waves are our privileged way to understand the world that surrounds us. The study and the simulation of wave propagation phenomena constitute a very broad and active field of research in various domains of physics and engineering sciences. The variety and the complexity of the underlying problems, their scientific and industrial interest, the existence of a common mathematical structure to these problems from different areas altogether justify a research project in applied mathematics and scientific computing devoted to this topic.

2.2. POEMS activities

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

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

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

3. Research Program

3.1. General description

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

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

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

3.2. New schemes for time-domain simulations

Problems of wave propagation naturally arise as problems of evolution and it is necessary to have efficient methods for the calculation of their solution, directly in the time domain. The development and analysis of such methods has been in the past an important part of POEMS activity. Nowadays, there exists a large variety of higher order numerical methods that allow us to solve with good accuracy and in short computational time most classical wave propagation problems.

However, when one wishes to deal with real life applications, one has to tackle problems which are complex in many ways: they involve multi-physics, non standard (possibly nonlinear) constitutive laws, highly heterogeneous media with high contrasts of coefficients, complex geometries... In many cases, such problems escape to the direct application of the above mentioned methods and *ad hoc* dedicated methods have to be designed.

Such methods are most often of hybrid nature, which includes domain decomposition methods and subgridding, mixing of integral equations and PDEs, and artificial boundary conditions. In time domain, a particularly challenging issue is the time stability, in particular concerning the coupling of algorithms. To cope with this major difficulty, a key issue (and a kind of Grail for numerical analysts) is the development of energy preserving methods which is one of the specificity of the research developed at POEMS in this field.

3.3. Integral equations

Our activity in this field aims at developing accurate and fast methods for 3D acoustic and elastodynamic problems based on the discretization of boundary integral equations.

In traditional implementation, the dimensional advantage of Boundary Element Methods (BEM) with respect to domain discretization methods is offset by the fully-populated nature of the BEM matrix. Various approaches such as the Fast Multipole Method (FMM) or hierarchical matrices (H-matrices) have been proposed to overcome this drawback and derive fast BEMs. The specificity of our work consists in deriving such approaches not only for 3D acoustic wave propagation but also for 3D elastodynamics with applications in soil-structure interaction, seismology or seismic imaging.

Since the solution is computed through an iterative solver, a crucial point is then to control the number of iterations as the problem complexity increases, through the development of adapted preconditioners.

Besides, we also try to hybridize integral equations and high-frequency methods for scattering problems ,in order to tackle configurations with scatterers of different size-scales, compared to the wavelength.

Finally, we have studied the relationship between the Maxwell and eddy current models for three-dimensional configurations involving highly-conducting bounded bodies in air and sources placed remotely from those bodies

3.4. Domain decomposition methods

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

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

One ANR project (NonLocalDD) supports this research.

3.5. Wave propagation in complex media

Our objective is first to develop efficient numerical approaches for the propagation of waves in heterogeneous media, taking into account their complex microstructure.

We aim on one hand to improve homogenized modeling of periodic media, by deriving enriched boundary conditions (or transmission conditions if the periodic structure is embedded in a homogeneous matrix) which take into account the boundary layer phenomena. On the other hand, we like to develop multi-scale numerical methods when the assumption of periodicity on the spatial distribution of the heterogeneities is relaxed, or even completely lost. The general idea consists in a coupling between a macroscopic solver, based on a coarse mesh, with some microscopic representation of the field. This latter can be obtained by a numerical microscopic solver or by an analytical asymptotic expansion. This leads to two very different approaches which may be relevant for very different applications.

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

3.6. Spectral theory and modal approaches

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

Then, we would like to go further in proving the absence of localized modes in non uniform open waveguides. An original approach has been successfully applied to the scalar problem of a waveguides junctions or bent waveguides. The challenge now is to extend these ideas to vectorial problems (for applications to electromagnetism or elastodynamics) and to junctions of periodic waveguides.

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

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

3.7. Inverse problems

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

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

An originality of our activity is to consider inverse scattering in waveguides (the inverse scattering community generally considers only free-space configurations). This is motivated at the same time by specific issues concerning the ill-posedness of the identification process and by applications to non-destructive techniques, for waveguide configurations (cables, pipes, plates etc...). In particular, with the help of experimental data obtained at CEA-List, we proved the feasibility of the Linear Sampling Method to identify defects in the context of ultrasonic NDT.

Lastly, we continued our work on the so-called exterior approach for solving inverse obstacle problems, which associates quasi-reversibility and level set methods. We extended such approach to evolution problems, in particular the wave equation in the time domain for a finite time interval.

4. Application Domains

4.1. Acoustics

Two particular subjects have retained our attention recently.

1. Aeroacoustics, or more precisely, acoustic propagation in a moving compressible fluid, has been for our team a very challenging topic, which gave rise to a lot of open questions, from the modeling until the numerical approximation of existing models. Our works in this area are partially supported by Airbus. The final objective is to reduce the noise radiated by Airbus planes.
2. Musical acoustics constitute a particularly attractive application. We are concerned by the simulation of musical instruments whose objectives are both a better understanding of the behavior of existing instruments and an aid for the manufacturing of new instruments. We have successively considered the timpani, the guitar and the piano.

4.2. Electromagnetism

Applied mathematics for electromagnetism during the last ten years have mainly concerned stealth technology and electromagnetic compatibility. These areas are still motivating research in computational sciences (large scale computation) and mathematical modeling (derivation of simplified models for multiscale problems). Electromagnetic propagation in non classical media opens a wide and unexplored field of research in applied mathematics. This is the case of wave propagation in photonic crystals, metamaterials or magnetized plasmas. Finally, the simulation electromagnetic (possibly complex, even fractal) networks is motivated by destructive testing applications. These topics are developed in collaboration with CEA, DGA and ONERA.

4.3. Elastodynamics

Wave propagation in solids is with no doubt, among the three fundamental domains that are acoustics, electromagnetism and elastodynamics, the one that poses the most significant difficulties from mathematical and numerical points of view. A major application topic has emerged during the past years : the non destructive testing by ultra-sounds which is the main topic of our collaboration with CEA-LIST. On the other hand, we are developing efficient integral equation modelling for geophysical applications (soil-structure interaction for civil engineering, seismology).

5. Highlights of the Year

5.1. Highlights of the Year

- POEMS project-team reached the deadline of 12 years at the end of 2017. We have devoted a large part of our time during the first half-year to conceive and write a text of 20 pages which describes the new project that we submit to the management of Inria, in order to pursue our research on the modeling and simulation of wave phenomena. This project is currently discussed by several experts, in interaction with ourselves, before the final decision of creation of the new project-team.
- S. Chaillat co-organized with X. Claeys (Sorbonnes & EPI ALPINES) the symposium of the *International Association for Boundary Element Methods (IABEM)*, which took place in Paris in June 2018. There were about 140 attendees.
- A.-S. Bonnet-Ben Dhia co-organized a workshop entitled *“Advanced Theoretical and Numerical Methods for waves in structured Media”* in Paris in March 2018, in the framework of the GDR Ondes. There were about 90 attendees.
- P. Ciarlet is co-author of a book entitled *"Mathematical Foundations of Computational Electromagnetism"*, published in the serie *Applied Mathematical Sciences* by Springer.

6. New Software and Platforms

6.1. XLiFE++

KEYWORDS: Numerical simulations - Finite element modelling - Boundary element method
FUNCTIONAL DESCRIPTION: XLiFE++ is an FEM-BEM C++ code developed by POEMS laboratory and IRMAR laboratory, that can solve 1D/2D/3D, scalar/vector, transient/stationary/harmonic problems. Description: https://uma.ensta-paristech.fr/soft/XLiFE++/

- Contact: Eric Lunéville

6.2. COFFEE

KEYWORDS: Numerical simulations - Wave propagation - Boundary element method
FUNCTIONAL DESCRIPTION: COFFEE is an adapted fast BEM solver to model acoustic and elastic wave propagation (full implementation in Fortran 90). The 3-D acoustic or elastodynamic equations are solved with the boundary element method accelerated by the multi-level fast multipole method or a hierarchical-matrices based representation of the system matrix. The fundamental solutions for the infinite space are used in this implementation. A boundary element-boundary element coupling strategy is also implemented so multi-region problems (strata inside a valley for example) can be solved. In order to accelerate the convergence of the iterative solver, various analytic or algebraic preconditioners are available. Finally, an anisotropic mesh adaptation strategy is used to further reduce the computational times.

- Contact: Stéphanie Chaillat

7. New Results

7.1. New schemes for time-domain simulations

7.1.1. Solving the Isotropic Linear Elastodynamics Equations Using Potentials

Participant: Patrick Joly.

This work is done in collaboration with Sébastien Impériale (EPI M3DISIM) and Jorge Albella and Jeronimo Rodríguez from the University of Santiago de Compostela.

We pursue our research on the numerical solution of 2D elastodynamic equations in piecewise homogeneous media using the decomposition of the displacement fields into the sum of the gradient and the rotational (respectively) of two scalar potentials potentials. This allows us to obtain an automatic decomposition of the wave field into the sum of pressure and shear waves (respectively). The approach is expected to be efficient when the velocity of shear waves is much smaller than the velocity of pressure waves, since one can adapt the discretization to each type of waves. This appears as a challenge for finite element methods , the most delicate issue being the treatment of boundary and transmission conditions, where the two potentials are coupled..

A stable (mixed) variational formulation of the evolution problem based on a clever choice of Lagrange multipliers has been proposed as well as various finite element approximations which have been successfully implemented. The analysis of the continuous problem has been published in a long paper in the journal of Scientific computing.The numerical analysis of the discretized problem is in progress.

7.1.2. Time domain Half-Space Matching method

Participants: Sonia Fliss, Hajer Methenni.

This work is done in the framework of the PhD of Hajer Methenni (funded by CEA-LIST) and in collaboration with Sebastien Imperiale (EPI M3DISIM) and Alexandre Imperiale (CEA-LIST).

The objective of this work is to propose a numerical method to solve the elastodynamics equations in a locally perturbed unbounded anisotropic media. Let us mention that all the classical methods to restrict the computation around the perturbations are unstable in anisotropic elastic media (PMLs for instance) or really costly (Integral equations). The idea is to extend the method already developed for the corresponding time harmonic problem, called the Halfspace Matching Method. We have considered, for now, the 2D scalar wave equation but the method is constructed in order to be applied to the elastodynamic problem. The method consists in coupling several representations of the solution in half-planes surrounding the defect with a FE representation in a bounded domain including the defect. In order to ensure the stability of the method, we first semi-discretize in time the equations and apply the method to the semi-discrete problem. Thus, for each time step, by ensuring that all the representations of the solution match, in particular in the intersection of the half-planes, we end up, at each time step, with a system of equations which couples, via integral operators, the solution at this time step in the bounded domain and its traces on the edge of the half-planes, the right hand side being a convolution operator involving the solution at the previous time steps. The method has been implemented and validated with Xlife++.

We are now looking to make the method more efficient by implementing methods of acceleration. Finally, we will also seek to develop another version of the method based on the Convolution quadrature.

7.1.3. Time domain modelling for wave propagation in fractal trees

Participants: Patrick Joly, Maryna Kachanovska.

In order to simulate wave propagation in fractal trees (see section 7.4.3), which have infinite structure, it is necessary to be able to truncate the computations to a finite subtree. This was done using Dirichlet-to-Neumann (DtN) operators in our previous work in collaboration with A. Semin (TU Darmstadt). In this case a DtN operator is a convolution operator, whose kernel is not known in a closed form. Based on the results of this previous work, in 2017 we had proposed two methods for approximating these convolution operators:

- constructing an exact DtN operator for a semi-discretized system (in the spirit of convolution quadrature methods).
- truncating meromorphic expansion for the symbol (Fourier transform of the convolution kernel) of the DtN operator, which allows to approximate the DtN operator by local operators.

This year we have performed a complete convergence and stability analysis of these methods, based on the energy techniques.

In particular, for the convolution quadrature methods, we were able to obtain all the estimates using time-domain analysis, by avoiding passage to the Laplace domain.

As for the method based on the meromorphic expansion of the symbol of the DtN operator, we have shown that the error induced by truncating the expansion to L terms can be controlled by a remainder of a series, which, in particular, depends on the eigenvalues of the weighted Laplacian on the fractal trees. To obtain an explicit dependence of the error on L, we have computed Weyl bounds for the eigenvalues, based on a refinement of the ideas of [Kigami, Lapidus, Comm. Math. Phys. 158 (1993)].

Additionally, we have addressed some computational aspects of the two methods, in particular, efficient evaluation of the symbol of the DtN operator (we have an algorithm that allows to evaluate it at the frequency ω in $O(\log^k |\omega|)$ time), as well as a method for efficient computation of the poles of the symbol (based on Möbius transform and polynomial interpolation).

7.2. Integral equations and boundary element methods (BEMs)

7.2.1. Accelerated and adapted BEMs for wave propagation

Participants: Faisal Amlani, Stéphanie Chaillat.

This work is done in collaboration with Adrien Loseille (EPI Gamma3).

We extend to high-order curved elements a recently introduced metric-based anisotropic mesh adaptation strategy for accelerated boundary element methods (e.g. Fast Multipole(FM-) BEM) applied to exterior boundary value problems. This method derives from an adaptation framework for volumetric finite element methods and is based on an iterative procedure that completely remeshes at each refinement step and that leads to a strategy that is independent of discretization technique (e.g., collocation or Galerkin) and integral representation (e.g., single- or double-layer). In effect, it results in a truly anisotropic adaptation that alters the size, shape and orientation of each element according to an optimal metric based on a numerically recovered Hessian of the boundary solution. The algorithm is principally characterized by its ability to recover optimal convergence rates for both flat and curved discretizations (e.g. P_0-, P_1- or P_2-elements) of a geometry containing singularities such as corners and edges. This is especially powerful for realistic geometries that include engineering detail (whose solutions often entail severe singular behavior).

Additionally, we address — by way of introducing hierarchical ($\mathcal{H}$-) matrix preconditioning applied to fast multipole methods via a Flexible GMRES (FGMRES) routine — the computational difficulties that arise when resolving highly anisotropic (and hence highly ill-conditioned) linear systems. The new technique, which uses a very coarse $\mathcal{H}$-matrix system (constructed rapidly via high-performance parallelization) to precondition the full Fast Multipole Method system, drastically reduces the overall computation time as well as the iterative solve time, further improving the tractability of addressing even larger and more complex geometries by FM-BEM.

7.2.2. Preconditioned $\mathcal{H}$-matrix based BEMs for wave propagation

Participants: Stéphanie Chaillat, Patrick Ciarlet, Félix Kpadonou.

We are interested with fast boundary element methods (BEMs) for the solution of acoustic and elastodynamic problems.

The discretisation of the boundary integral equations, using BEM, yields to a linear system, with a fully-populated matrix. Standard methods to solve this system are prohibitive in terms of memory requirements and solution time. Thus one is rapidly limited in terms of complexity of problems that can be solved. The $\mathcal{H}$-matrix based BEMs is commonly used to address these limitations. It is a purely algebraic approach.

The starting point is that the BEM matrix can be partitioned into some blocks which can either be of low or full rank. Memory can be saved by using low-rank revealing technique such as the Adaptive Cross Approximation. We have already study the efficiency of this approach for wave propagation problems. The purpose being the applications to large scale problems, we are now interested in an efficient implementation of the solver in a high performance computing setting. Thus, a bottleneck, with an hierarchical matrix data-sparse representation, is the management of the memory and its (prior) estimation for array allocations.

The first part of our work has been devoted to the proposition of an a priori estimation of the ranks of the blocks in the hierarchical matrix. Afterwards, we have implemented a parallel construction of the $\mathcal{H}$-matrix representation and H-matrix vector product (basic operation in any iterative solver), using a multi-threading OpenMP parallelization. The solution is then computed through the GMRES iterative solver. A crucial point is then the solution time of that solver and the number of iterations as the problem complexity increases. We have developed a two-level, nested outer-inner, iterative solver strategy. The inner solver preconditioned the outer. The preconditioner is a coarse data-sparse representation of the BEM system matrix.

7.2.3. Coupling integral equations and high-frequency methods

Participants: Marc Bonnet, Marc Lenoir, Eric Lunéville, Laure Pesudo.

This theme concerns wave propagation phenomena which involve two different space scales, namely, on the one hand, a medium scale associated with lengths of the same order of magnitude as the wavelength (medium-frequency regime) and on the other hand, a long scale related to lengths which are large compared to the wavelength (high-frequency regime). Integral equation methods are known to be well suited for the former, whereas high-frequency methods such as geometric optics are generally used for the latter. Because of the presence of both scales, both kinds of simulation methods are simultaneously needed but these techniques do not lend themselves easily to coupling.

The scattering of an acoustic wave by two sound-hard obstacles: a large obstacle subject to high-frequency regime relatively to the wavelength and a small one subject to medium-frequency regime has been investigated by Marc Lenoir, Eric Lunéville and Laure Pesudo. The technique proposed in this case consists in an iterative method which allows to decouple the two obstacles and to use Geometric Optics or Physical Optics for the large obstacle and Boundary Element Method for the small obstacle. This approach has been validated on various situations using the XLife++ library developed in the lab. When the obstacles are not sticked, even if they are very close, the iterative method coupling BEM and some high-frequency methods (ray approximation or Kirchoff approximation) works very well. When the obstacle are sticked, the "natural" iterative method is no longer convergent. We are currently looking for some improved methods to deal with these cases that have a practical interest.

7.2.4. *The eddy current model as a low-frequency, high-conductivity asymptotic form of the Maxwell transmission problem*

Participant: Marc Bonnet.

In this work, done in collaboration with Edouard Demaldent (CEA LIST), we study the relationship between the Maxwell and eddy current (EC) models for three-dimensional configurations involving highly-conducting bounded bodies in air and sources placed remotely from those bodies. Such configurations typically occur in the numerical simulation of eddy current non destructive testing (ECT). The underlying Maxwell transmission problem is formulated using boundary integral formulations of PMCHWT type. In this context, we derive and rigorously justify an asymptotic expansion of the Maxwell integral problem with respect to the non-dimensional parameter $\gamma := \sqrt{\omega\varepsilon_0/\sigma}$. The EC integral problem is shown to constitute the limiting form of the Maxwell integral problem as $\gamma \to 0$, i.e. as its low-frequency and high-conductivity limit. Estimates in γ are obtained for the solution remainders (in terms of the surface currents, which are the primary unknowns of the PMCHWT problem, and the electromagnetic fields) and the impedance variation measured at the extremities of the excitating coil. In particular, the leading and remainder orders in γ of the surface currents are found to depend on the current component (electric or magnetic, charge-free or not). Three-dimensional illustrative numerical simulations corroborate these theoretical findings.

7.2.5. *Modelling the fluid-structure coupling caused by a far-field underwater explosion*

Participants: Marc Bonnet, Stéphanie Chaillat, Damien Mavaleix-Marchessoux.

This work, funded by Naval Group and a CIFRE PhD grant, addresses the computational modelling of the mechanical effect on ships of remote underwater explosions. We aim at a comprehensive modelling approach that accounts for the effect of the initial (fast) wave impinging the ship as well as that of later, slower, water motions. Both fluid motion regimes are treated by boundary element methods (respectively for the wave and potential flow models), while the structure is modelled using finite elements. To cater for large and geometrically complex structures, the BEM-FEM interface requires large numbers of DOFs, which entails the use of a fast BEM solver. Accordingly, the wave-like fluid motions are to be computed by means of the convolution quadrature method (CQM) implemented in the in-house fast BEM code COFFEE. This work is in progress (the thesis having started in Dec. 2017). Work accomplished so far has mainly consisted in (a) thoroughly examinating the physical modelling issues, (b) formulating the mathematical and computational model that takes relevant physical features into account, and (c) implementing and assessing the CQM under conditions similar to those of the aimed application.

7.3. Domain decomposition methods

7.3.1. *Transparent boundary conditions with overlap in unbounded anisotropic media*

Participants: Anne-Sophie Bonnet Ben-Dhia, Sonia Fliss, Yohanes Tjandrawidjaja.

This work is done in the framework of the PhD of Yohanes Tjandrawidjaja (funded by CEA-LIST), in collaboration with Vahan Baronian (CEA). This follows the PhD of Antoine Tonnoir (now Assistant Professor at Insa of Rouen) who developed a new approach, the Half-Space Matching Method, to solve scattering problems in 2D unbounded anisotropic media. The objective is to extend the method to a 3D plate of finite width.

In 2D, our approach consists in coupling several plane-waves representations of the solution in half-spaces surrounding the defect with a FE computation of the solution around the defect. The difficulty is to ensure that all these representations match, in particular in the infinite intersections of the half-spaces. It leads to a formulation which couples, via integral operators, the solution in a bounded domain including the defect and some traces of the solution on the edges of the half-planes. We have proven that, in presence of dissipation, this system is a Fredholm equation of the second kind, in an L2 functional framework. The truncation of the Fourier integrals and the finite element approximation of the corresponding numerical method have been also analyzed.

The method has been extended to the 3D case, for an application to non-destructive testing. The objective is to simulate the interaction of Lamb waves with a defect in an anisotropic elastic plate. The additional complexity compared to the 2D case lies in the representations which are obtained semi-analytically by decomposition on Lamb modes. In addition, the system of equations couples the FE representation in the bounded perturbed domain with not only the displacement, but also the normal stress of the solution on the infinite bands limiting the half-plates. A first numerical result has been obtained in the isotropic case.

The perspectives now concern the efficiency of the method (which could be improved by replacing the direct inversion by a preconditioned iterative inversion with an efficient product matrix-vector), the analysis of the method in the case without dissipation and the analysis of the method in the elastic case.

7.3.2. Coupling BEMs in overlapping domains when a global Green's function is not available

Participants: Anne-Sophie Bonnet Ben-Dhia, Stéphanie Chaillat, Sonia Fliss, Yohanes Tjandrawidjaja.

We consider in this work problems for which the Green's function is not available, so that classical Boundary Integral equation methods are not applicable. Let us mention for instance the junction of two different stratified media (tapered optical fibers in integrated optics or junction of two topographic elastic surfaces in geophysics).

To this end, we propose a generalization of the Half-Space Matching method (see section 7.3.1).

In this work, by replacing the Fourier representations by integral representations, we are able to replace the half-spaces by more general unbounded overlapping sub-domains. We choose the sub-domains in such a way that an explicit Green's function is available for each subdomain. For instance, for the configuration described above (figure 1a), it suffices to introduce two infinite sub domains, each of them containing only one stratification (figures 1c and 1d) and a bounded domain containing the junction (figure 1b). The formulation couples the solution in the bounded domain with the single and double layer potentials on each boundary of the sub-domains. The approximation relies on a FE discretisation of the volume unknown and a truncation and a discretization of the boundary/surface unknowns.

A study concerning the choice of the discretisation parameters and the shape of the infinite lines have to be done. The theoretical analysis of the method raises challenging open questions: for instance, a first uniqueness result has been derived, which requires the definition of a variational formulation on a Rie. Finally, we want to apply the method to the scattering by a step, i.e. the junction of two semi infinite-planes joined together by a step.

7.3.3. Domain decomposition method for acoustics with uniform exponential rate of convergence using non-local impedance operators

Participants: Patrick Joly, Francis Collino, Émile Parolin.

This work is done in the framework of the PhD of Émile Parolin (funded by ANR NonlocalDD), in collaboration with X. Claeys (EPI Alpines & LJLL).

We continued the work on non-overlapping domain decomposition methods with non-local transmission conditions for time-harmonic wave propagation. The analysis of such methods is conducted by writing them as a relaxed Jacobi algorithm. In the absence of junctions points, the continuous algorithm converges exponentially fast under suitable assumptions on the impedance operators. These assumptions cannot be satisfied using local operators and rely in practice on singular integral operators. The progress achieved is as follows.

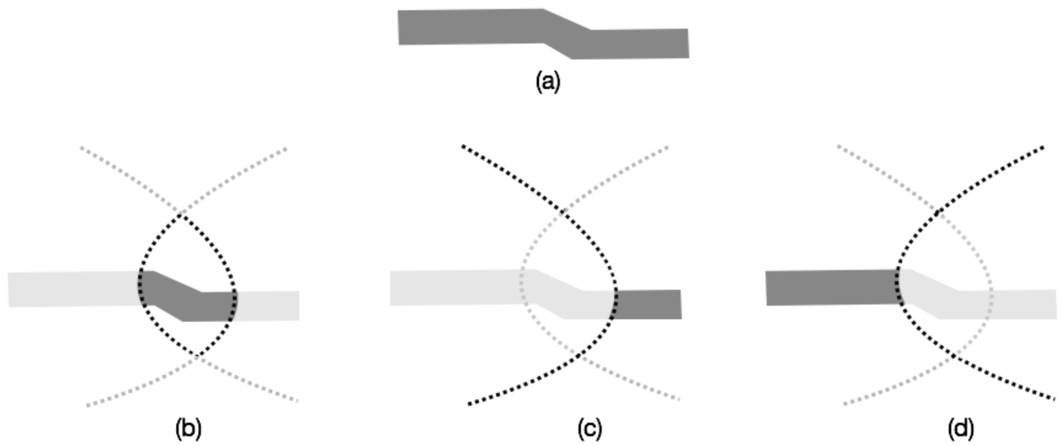

Figure 1. Coupling BEMs in overlapping domains

- In the context of acoustic wave propagation, we established a new result on the robustness of the algorithm with respect to the mesh size. We have proven that for Lagrange finite element approximations the exponential rate of convergence of the algorithm is independent of the discretization parameter, hence does not deteriorate when the mesh is refined. The proof relies on the Scott-Zhang interpolator and led to the submission.
- We have been working on the extension to 3D time harmonic Maxwell's equations. The main difficulty is to design well adapted operators taking into account the specificity of the corresponding trace spaces. An adequate operator must behave like a pseudo-differential operator with opposite order on the 'curl part' and 'grad part' of a tangential field (this is related to the Helmholtz decomposition of tangential fields). Guided by potential theory for elliptic operators, we proposed two classes of suitable operators. The first one is based on Bessel potentials (fractional powers of the shifted Laplacian) and the second one relies on Riesz potentials. We have shown that the proposed operators satisfy the desired properties in the case of a sphere using modal analysis techniques. We have also been working on the design of the finite element approximation of these operators.

7.3.4. Domain decomposition method with cross-point treatment for high-frequency acoustic scattering

Participant: Axel Modave.

This work is done in collaboration with X. Antoine (IECL & EPI SPHINX) and C. Geuzaine (Université de Liège).

Solving high-frequency time-harmonic scattering problems using FE techniques is challenging, as such problems lead to very large, complex and indefinite linear systems. Optimized Schwarz domain decomposition methods (DDMs) are currently a very promising approach, where subproblems of smaller sizes are solved in parallel using direct solvers, and are combined in an iterative procedure. It is well-known that the convergence rate of these methods strongly depends on the transmission condition enforced on the interfaces between the subdomains.

Local transmission conditions based on high-order absorbing boundary conditions (HABCs) have proved well suited. They represent a good compromise between basic impedance conditions (which lead to suboptimal convergence) and the exact Dirichlet-to-Neumann (DtN) map related to the complementary of the subdomain (which is expensive to compute). However, a direct application of this approach for domain decomposition configurations with cross-points, where more than two subdomains meet, does not provide satisfactory results.

We work on improved DDMs that efficiently addresses configurations with cross-points. Noting that these points actually are corners for the subdomains, our strategy consists in incorporating a corner treatment developed for HABCs (see section 7.7.1) into the DDM procedure. We propose a cross-point treatment for HABC-based DDMs in settings with cross-points and right angles. The method is implemented and successfully tested for two-dimensional examples. The analysis of this method is currently in progress. Extensions to more complicated settings (e.g. 3D, with non-right angles, other physical waves) will be investigated in the future.

7.4. Wave propagation in complex media

7.4.1. Enriched Homogenization in presence of boundaries or interfaces

Participants: Clement Beneteau, Sonia Fliss.

This work is done in the framework of the PhD of Clement Beneteau and is done in collaboration with X. Claeys (Sorbonne & EPI Alpines).

This work is motivated by the fact that classical homogenization theory poorly takes into account interfaces or boundaries. It is particularly unfortunate when one is interested in phenomena arising at the interfaces or the boundaries of the periodic media (the propagation of plasmonic waves at the surface of metamaterials for instance). To overcome this limitation, we have constructed an effective model which is enriched near the interfaces and/or the boundaries. For now, we have treated and analysed the case of simple geometries: for instance a half-plane with Dirichlet or Neumann boundary conditions or a plane interface between two periodic half spaces. We have derived a high order approximate model which consists in replacing the periodic media by an effective one but the boundary/transmission conditions are not classical. The obtained conditions involve Laplace- Beltrami operators at the interface and requires to solve cell problems in periodicity cell (as in classical homogenization) and in infinite strips (to take into account the phenomena near the boundary/interface). We establish well posedness for the approximate model and error estimates which justify that this new model is more accurate. From a numerical point of view, the only difficulty comes from the problems set in infinite strips. The method has been implemented using Xlife++.

This approach has been extended to the long time homogenisation of the wave equation. It is well known that the classical effective homogenized wave equation does not capture the long time dispersive effects of the waves in the periodic media. Since the works of Santosa and Symes in the 90's, several effective equations (involving differential operators of order at least 4) that capture these dispersive effects have been proposed, but only in infinite media. In presence of boundaries or interfaces, the question of boundary/transmission conditions for these effective equations was never treated. We have first results in that direction.

7.4.2. Transmission conditions between homogeneous medium and periodic cavities

Participant: Jean-François Mercier.

In collaboration with A. Maurel (Langevin Institute), J. J. Marigo (LMS) and K. Pham (Imsia).

We have developed a model for resonant arrays of Helmholtz cavities, thanks to a two scale asymptotic analysis. The model combines volumic homogenization to replace the cavity region by a homogeneous anisotropic slab and interface homogenization to replace the region of the necks by transmission conditions. The coefficients entering in the effective wave equation are simply related to the fraction of air in the periodic cell of the array. Those involved in the jump conditions encapsulate the effects of the neck geometry.

In parallel, this effective model has been exploited to study the resonance of the Helmholtz resonators with a focus on the influence of the neck shape. The homogenization makes a parameter B to appear which determines unambiguously the resonance frequency of any neck. As expected, this parameter depends on the length and on the minimum opening of the neck, and it is shown to depend also on the surface of air inside the neck. Once these three geometrical parameters are known, B has an additional but weak dependence on the neck shape, with explicit bounds.

7.4.3. *Mathematical analysis of wave propagation in fractal trees*

Participants: Patrick Joly, Maryna Kachanovska.

We have continued our work (in collaboration with A. Semin (TU Darmstadt)) on wave propagation in fractal trees which model human lungs. One of the major results of this year is a complete analysis of such models. In particular, provided Sobolev spaces H^1_μ, L^2_μ (which generalize weighted Sobolev spaces on an interval to the case of fractal trees) we clarified the following questions for a range of parameters of the trees not covered by the previous theory: existence of traces of H^1_μ-functions on fractal trees; approximation of H^1_μ-functions by compactly supported functions; compact embedding of H^1_μ into L^2_μ.

7.4.4. *Hyperbolic Metamaterials in Frequency Domain: Free Space*

Participants: Patrick Ciarlet, Maryna Kachanovska.

In this project we consider the wave propagation in 2D hyperbolic metamaterials [Poddubny et al., Nature Photonics, 2013], which are modelled by Maxwell equations with a diagonal frequency-dependent tensor of dielectric permittivity ε and scalar frequency-independent magnetic permeability. In the time domain, the corresponding models are well-posed and stable. Surprisingly, in some regimes in the frequency domain, when the signs of the diagonal entries of ε do not coincide, the problem becomes hyperbolic (and hence the name). The main goal of this project is to justify the well-posedness of such models in the frequency domain, first of all starting with the case of the free space. We have obtained partial results in this direction: radiation condition, which ensures the well-posedness of the problem, mapping properties of the resolvent (with refined estimates on the propagation of singularities in these models). We are currently working on the limiting absorption and limiting amplitude principles.

7.5. Spectral theory and modal approaches for waveguides

7.5.1. *Scattering solutions in an unbounded strip governed by a plate model*

Participants: Laurent Bourgeois, Sonia Fliss.

Together with Lucas Chesnel (EPI DEFI), we have initiated a new work on a particular waveguide which consists of a thin strip governed by a Kirchhoff-Love bilaplacian model. The aim is to build some radiation conditions and prove well-posedness of scattering problems for that simple model and for two kinds of boundary conditions: the strip is either simply supported or clamped. In the first case, we have shown that using a Dirichlet-to-Neumann operator enables us to prove fredholmness. Such approach is not possible in the second case, for which a completely different angle of attack is chosen: a Kondratiev approach involving weighted Sobolev spaces and detached asymptotics.

7.5.2. *Modal analysis of electromagnetic dispersive media*

Participants: Christophe Hazard, Sandrine Paolantoni.

We investigate the spectral effects of an interface between vacuum and a negative material (NM), that is, a dispersive material whose electric permittivity and/or magnetic permeability become negative in some frequency range. Our first work in this context concerns an elementary situation, namely, a two-dimensional scalar model (derived from the complete Maxwell's equations) which involves the simplest existing model of NM, referred to as the non-dissipative Drude model (for which negativity occurs at low frequencies). By considering a polygonal cavity, we have shown that the presence of the Drude material gives rise to various components of an essential spectrum corresponding to various unusual resonance phenomena: first, a low frequency bulk resonance (accumulation at the zero frequency of positive eigenvalues whose associated eigenvectors are confined in the Drude material); then, a surface resonance for one particular critical frequency (at which the so-called surface plasmons occurs, that is, localized highly oscillating vibrations at the interface between the Drude material and the vacuum); finally, corner resonances in a critical frequency interval (here, localized highly oscillating vibrations occur near any corner of the interface, interpreted as a "black hole" phenomenon). An article which presents these results has been submitted. Most recent works were devoted to the numerical simulation of these resonance phenomena in the context of the code XLiFE++ developped in the lab.

7.5.3. Formulation of invisibility in waveguides as an eigenvalue problem

Participant: Anne-Sophie Bonnet-Ben Dhia.

This work is done in collaboration with Lucas Chesnel from EPI DEFI and Vincent Pagneux from Laboratoire d'Acoustique de l'Université du Maine.

We consider an infinite acoustic waveguide (with a bounded cross-section) which is locally perturbed. At some exceptional frequencies and for particular incident waves, it may occur that all the energy of the incident wave is transmitted, the only effect in reflection being a superposition of evanescent modes in the vicinity of the perturbation. We have proposed an approach for which these reflection-less frequencies appear directly as eigenvalues of a new problem. This problem is very similar to the formulation of the scattering problem using Perfectly Matched Layers, except a slight modification in the PML. Precisely, we use two conjugated dilation parameters, α in the outlet and $\overline{\alpha}$ in the inlet, in order to select outgoing waves in the outlet and ingoing waves in the inlet. In fact, we show that the real eigenfrequencies that are obtained correspond either to trapped modes or to reflection-less modes. In addition to this real spectrum, we find intrinsic complex frequencies, which also contain information about the quality of the transmission through the waveguide. Mathematically, the non-selfadjoint eigenvalue problem with conjugated PMLs has strange properties: the discreteness of the point spectrum is not stable by compact perturbations and pathological examples can be exhibited.

7.6. Inverse problems

7.6.1. Linear Sampling Method with realistic data in waveguides

Participants: Laurent Bourgeois, Arnaud Recoquillay.

Our activities in the field of inverse scattering in waveguides with the help of sampling methods has now a quite long history. Very recently, we have focused on elastodynamics and realistic data, that is surface data in the time domain. This has been the subject of the PhD of Arnaud Recoquillay. It was motivated by Non Destructive Testing activities for tubular structures and was the object of a partnership with CEA List (Vahan Baronian).

Our strategy consists in transforming the time domain problem into a multi-frequency problem by the Fourier transform. This allows us to take full advantage of the established efficiency of modal frequency-domain sampling methods. In particular, we have shown how to optimize the number of sources/receivers and the distance between them in order to obtain the best possible imaging results.

Our main achievement is an experimental validation of such approach in the presence of real data: the measurements were carried at CEA on steel plates with the help of piezoelectric sensors. The identification results are encouraging and pave the way of a future integration of sampling methods in real NDT activities.

7.6.2. The "exterior approach" to solve inverse obstacle problems

Participants: Laurent Bourgeois, Arnaud Recoquillay, Dmitry Ponomarev.

This work is done in collaboration with Jérémi Dardé (IMT Toulouse).

We consider some inverse obstacle problems in acoustics by using a single incident wave, either in the frequency or in the time domain. When so few data are available, a Linear Sampling type method cannot be applied. In order to solve those kinds of problem, we propose an "exterior approach", coupling a mixed formulation of quasi-reversibility and a simple level set method. In such iterative approach, for a given defect D, we update the solution u with the help of a mixed formulation of quasi-reversibility while for a given solution u, we update the defect D with the help of a level set method based on a Poisson problem. We have studied two cases. The first case concerns the waveguide geometry in the frequency domain. The second case concerns a bounded spatial set in the time domain when data are given in a finite time interval. This last case is challenging because it raises the (open) question of the minimal final time which is required to ensure uniqueness of the obstacle from the lateral Cauchy data.

7.6.3. Inverse acoustic scattering using high-order small-inclusion expansion of misfit function

Participant: Marc Bonnet.

This work concerns an extension of the topological derivative concept for 3D inverse acoustic scattering problems involving the identification of penetrable obstacles, whereby the featured data-misfit cost function J is expanded in powers of the characteristic radius a of a single small inhomogeneity. The $O(a^6)$ approximation of J is derived and justified for a single obstacle of given location, shape and material properties embedded in a 3D acoustic medium of arbitrary shape, and the generalization to multiple small obstacles is outlined. Simpler and more explicit expressions are obtained when the scatterer is centrally-symmetric or spherical. An approximate and computationally light global search procedure, where the location and size of the unknown object are estimated by minimizing the $O(a^6)$ approximation over a search grid, is proposed and demonstrated on numerical experiments, where the identification from known acoustic pressure on the surface of a penetrable scatterer embedded in a acoustic semi-infinite medium, and whose shape may differ from that of the trial obstacle assumed in the expansion of J, is considered. measurements configuration situated far enough from the probing region.

7.6.4. Microstructural topological sensitivities of the second-order macroscopic model for waves in periodic media

Participant: Marc Bonnet.

This work is done in collaboration with Bojan Guzina (University of Minnesota, USA) and Rémi Cornaggia (IRMAR, Rennes).

We consider scalar waves in periodic media through the lens of a second-order effective i.e. macroscopic description, and we aim to compute the sensitivities of the relevant effective parameters due to topological perturbations of a microscopic unit cell. Specifically, our analysis focuses on the tensorial coefficients in the governing mean-field equation – including both the leading order (i.e. quasi-static) terms, and their second-order counterparts. The results demonstrate that the sought sensitivities are computable in terms of (i) three unit-cell solutions used to formulate the unperturbed macroscopic model; (ii) two adoint-field solutions driven by the mass density variation inside the unperturbed unit cell; and (iii) the usual polarization tensor, appearing in the related studies of non-periodic media, that synthesizes the geometric and constitutive features of a point-like perturbation. The proposed developments may be useful toward (a) the design of periodic media to manipulate macroscopic waves via the microstructure-generated effects of dispersion and anisotropy, and (b) sub-wavelength sensing of periodic defects or perturbations.

7.6.5. Analysis of topological derivative as a tool for qualitative identification

Participant: Marc Bonnet.

This work is a collaboration with Fioralba Cakoni (Rutgers University, USA).

The concept of topological derivative has proved effective as a qualitative inversion tool for a wave-based identification of finite-sized objects. Although for the most part, this approach remains based on a heuristic interpretation of the topological derivative, a first attempt toward its mathematical justification was done in Bellis et al. (Inverse Problems 29:075012, 2013) for the case of isotropic media with far field data and inhomogeneous refraction index. Our paper extends the analysis there to the case of anisotropic scatterers and background with near field data. Topological derivative-based imaging functional is analyzed using a suitable factorization of the near fields, which became achievable thanks to a new volume integral formulation recently obtained in Bonnet (J. Integral Equ. Appl. 29:271-295, 2017). Our results include justification of sign heuristics for the topological derivative in the isotropic case with jump in the main operator and for some cases of anisotropic media, as well as verifying its decaying property in the isotropic case with near field spherical measurements configuration situated far enough from the probing region.

7.6.6. Elasticity imaging by error in constitutive equation functionals

Participant: Marc Bonnet.

This work is done in collaboration with Wilkins Aquino (Duke University, USA).

We formulate the identification of heterogeneous linear elastic moduli in the context of time-harmonic elastodynamics as the minimization of the modified error in constitutive equation (MECE) functional. Our main goal is to develop theoretical foundations, in a continuous setting, allowing to explain and justify some known beneficial properties of this treatment. A specific feature of MECE formulations is that forward and adjoint solutions are governed by a fully coupled system, whose mathematical properties play a fundamental role in the qualitative and computational aspects of MECE minimization. We prove that this system has a unique and stable solution at any frequency, provided data is abundant enough (in a sense made precise), even though the relevant forward problem is not *a priori* clearly defined. This result has practical implications such as applicability of MECE to partial interior data (with important practical applications including ultrasound elastography), convergence of finite element discretizations and differentiability of the reduced MECE functional. In addition, we establish that usual least squares and pure ECE formulations are limiting cases of MECE formulations for small and large values of the weight of the data misfit component of the functional, respectively. For the latter case, we furthermore show that the reduced MECE Hessian is asymptotically positive for any parameter perturbation supported on the measurement region, thereby corroborating existing computational evidence on convexity improvement brought by MECE functionals. Finally, numerical studies including parameter reconstruction examples using interior data support our findings.

7.6.7. A continuation method for building large invisible obstacles in waveguides

Participants: Antoine Bera, Anne-Sophie Bonnet-Ben Dhia.

This work is done on collaboration with Lucas Chesnel (EPI DEFI).

We are interested in building invisible obstacles in waveguides, at a given frequency. The invisibility is characterized by the nullity of the scattering coefficients associated to propagating modes. In previous papers, a method has been proposed to prove the existence of invisible obstacles and to build them. But its main drawback was its limitation to small obstacles. In order to get larger invisible obstacles, we have developed a new approach which combines the previous idea with a continuation method: we are building a sequence of invisible obstacles, each of them being a small perturbation of the previous one. This algorithm is based, at each step, on the ontoness of an application and on the fixed-point theorem. We have implemented the method in the finite element library XLiFE++, in the case of penetrable obstacles of a two-dimensional acoustic waveguide, in multi-modal regime. A remarkable result is that the ontoness condition can be ensured in many cases, so that the algorithm can be iterated as long as required. Another interesting feature of our approach is that it allows to prescribe some properties of the obstacle (shape of the obstacle, piecewise constant index, ...), but a drawback is that the algorithm can produce non-realistic negative indices. This is a question that we are currently working on. Finally, let us emphasize that the formalism of the method is very general and flexible. In particular, it can be directly extended to 3D waveguides, or to the scattering in free space.

7.7. Acoustics and aeroacoustics

7.7.1. High-order absorbing boundary conditions with corner treatment for high-frequency acoustic scattering

Participant: Axel Modave.

This work is done in collaboration with C. Geuzaine (University of Liège) and X. Antoine (IECL & EPI SPHINX)

We address the design and validation of accurate local absorbing boundary conditions set on convex polygonal computational domains for the finite element solution of high-frequency acoustic scattering problems. While high-order absorbing boundary conditions (HABCs) are accurate for smooth fictitious boundaries, the precision of the solution drops in the presence of corners if no specific treatment is applied. We analyze two strategies to preserve the accuracy of Padé-type HABCs at corners: first by using compatibility relations (derived for right angle corners) and second by regularizing the boundary at the corner. We show that the former strategy is well-adapted to right corners and efficient for nearly-right corners, while the later is better for very obtuse corners. Numerical results are proposed to analyze and compare the approaches for two-and three-dimensional problems.

7.7.2. Time-harmonic acoustic scattering in a vortical flow

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

We study the time-harmonic acoustic radiation in a fluid in flow. To go beyond the convected Helmholtz equation, only adapted to potential flows, we use Goldstein's equations, coupling exactly the acoustic waves to the hydrodynamic field. We have studied the hydrodynamic part of Goldstein equations, corresponding to a generalized time-harmonic transport equation and we have investigated its well-posedness. The result has been established under the assumption of a domain-filling flow, which in 2D is simply equivalent to a flow that does not vanish. The approach relies on the method of characteristics, which leads to the resolution of the transport equation along the streamlines and on general results of functional analysis. The theoretical results have been illustrated with numerical results obtained with a SUPG Finite Element scheme.

In complement we have developed a new model for Goldstein's equations in which the description of the hydrodynamic phenomena is simplified. The model, initially developed for a carrier flow of low Mach number M, is proved theoretically to remain accurate for moderate Mach numbers, associated to a low error bounded by M^2. Numerical experiments confirm the M^2 law and the good quality of the model for flows of non-small Mach numbers.

7.8. Numerical analysis for PDEs

7.8.1. A family of Crouzeix-Raviart Finite Elements in 3D

Participant: Patrick Ciarlet.

This work is done in collaboration with C. Dunkl (University of Virginia) and S. Sauter (Universität Zürich).

We develop a family of non-conforming "Crouzeix–Raviart" type finite elements in three dimensions. They consist of local polynomials of maximal degree p on simplicial finite element meshes while certain jump conditions are imposed across adjacent simplices. We will prove optimal a priori estimates for these finite elements. The characterization of this space via jump conditions is implicit and the derivation of a local basis requires some deeper theoretical tools from orthogonal polynomials on triangles and their representation. We will derive these tools for this purpose. These results allow us to give explicit representations of the local basis functions. Finally, we will analyze the linear independence of these sets of functions and discuss the question whether they span the whole non-conforming space.

7.8.2. Numerical analysis of the mixed finite element method for the neutron diffusion eigenproblem with heterogeneous coefficients

Participants: Patrick Ciarlet, Léandre Giret, Félix Kpadonou.

This work is done in collaboration with E. Jamelot (CEA).

We study first the convergence of the finite element approximation of the mixed diffusion equations with a source term, in the case where the solution is of low regularity. Such a situation commonly arises in the presence of three or more intersecting material components with different characteristics. Then we focus on the approximation of the associated eigenvalue problem. We prove spectral correctness for this problem in the mixed setting. These studies are carried out without, and then with a domain decomposition method. The domain decomposition method can be non-matching in the sense that the traces of the finite element spaces may not fit at the interface between subdomains. Finally, numerical experiments illustrate the accuracy of the method.

7.8.3. Localization of global norms and robust a posteriori error control for transmission problems with sign-changing coefficients

Participant: Patrick Ciarlet.

This work is done in collaboration with M. Vohralik (EPI SERENA).

We present a posteriori error analysis of diffusion problems where the diffusion tensor is not necessarily symmetric and positive definite and can in particular change its sign. We first identify the correct intrinsic error norm for such problems, covering both conforming and nonconforming approximations. It combines a dual (residual) norm together with the distance to the correct functional space. Importantly, we show the equivalence of both these quantities defined globally over the entire computational domain with the Hilbertian sums of their localizations over patches of elements. In this framework, we then design a posteriori estimators which deliver simultaneously guaranteed error upper bound, global and local error lower bounds, and robustness with respect to the (sign-changing) diffusion tensor. Robustness with respect to the approximation polynomial degree is achieved as well. The estimators are given in a unified setting covering at once conforming, nonconforming, mixed, and discontinuous Galerkin finite element discretizations in two or three space dimensions. Numerical results illustrate the theoretical developments.

7.8.4. On the convergence in H^1-norm for the fractional Laplacian

Participant: Patrick Ciarlet.

This work is done in collaboration with J.P. Borthagaray (University of Maryland).

We consider the numerical solution of the fractional Laplacian of index $s \in (1/2, 1)$ in a bounded domain Ω with homogeneous boundary conditions. Its solution a priori belongs to the fractional order Sobolev space $\widetilde{H}^s(\Omega)$. For the Dirichlet problem and under suitable assumptions on the data, it can be shown that its solution is also in $H^1(\Omega)$. In this case, if one uses the standard Lagrange finite element to discretize the problem, then both the exact and the computed solution belong to $H^1(\Omega)$. A natural question is then whether one can obtain error estimates in $H^1(\Omega)$-norm, in addition to the classical ones that can be derived in the $\widetilde{H}^s(\Omega)$ energy norm. We address this issue, and in particular we derive error estimates for the Lagrange finite element solutions on both quasi-uniform and graded meshes.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- Contract and CIFRE PhD with EDF on *the FEM-BEM coupling for soil-structure interactions*
  Participants: M. Bonnet, S. Chaillat, Z. Adnani
  Start: 11/2014. End: 02/2018. Administrator: CNRS
- Contract and CIFRE PhD with Airbus on *time-harmonic acoustic scattering in a vortical flow*
  Participants: P. Joly, J.-F. Mercier, A. Bensalah
  Start: 10/2014, End: 04/2018. Administrator: ENSTA
- Contract and CIFRE PhD with Naval Group on *modelling the fluid-structure coupling caused by a far-field underwater explosion*
  Participants: M. Bonnet, S. Chaillat, D. Mavaleix-Marchessoux
  Start: 11/2017. End: 10/2020. Administrator: CNRS
- Contract and CIFRE PhD with Naval Group on *flow noise prediction*
  Participants: J-F Mercier, S. Cotté, N. Trafny
  Start: 04/2018. End: 03/2021. Administrator: ENSTA

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

- ANR project NonlocalDD *(Non-local domain decomposition methods in electromagnetics)*
  Partners: Inria Alpines, Inria POEMS, Inria Magique 3D
  Start: 10/2015. End: 09/2019. Administrator: Inria
  Participants of POEMS: S. Chaillat, P. Joly
  Coordinator: X. Claeys (LJLL, EPI ALPINES)
- ANR project MODULATE *(Modeling lOng-perioD groUnd motions, and assessment of their effects on Large-scale infrAsTructurEs)*
  Partners: ENSTA (UME), Inria POEMS, CentraleSupelec, BRGM, GDS
  Start: 11/2018. End: 10/2021. Administrator: ENSTA
  Participant of POEMS: S. Chaillat
  Coordinator: K. Meza Fajardo (BRGM)

9.1.2. DGA

- Contracts between DGA and POEMS:
  - Contract on *inverse problems*
    Participants: L. Bourgeois
    Start: 10/2016. End: 09/2018. Administrator: ENSTA
  - Contract on *boundary element methods and high-frequency problems*
    Participants: E. Lunéville, M. Lenoir, N. Kielbasiewicz.
    Start: 10/2015. End: 2021. Administrator: ENSTA
    In partnership with F. Alouges and M. Aussal (CMAP, Ecole Polytechnique).
  - Contract on *the preconditioning of fast BEM solvers*
    Participants: S. Chaillat, F. Amlani
    Start: 10/2017. End: 12/2018. Administrator: ENSTA
- DGA provides partial funding for several PhD students:
  - A. Bera on the *design of invisible obstacles for acoustic and electromagnetic waves* (Start: 10/2016)
  - C. Beneteau on the *asymptotic analysis of time harmonic Maxwell equations in presence of metamaterials* (Start: 10/2017)
  - D. Chicaud on *domain decomposition methods for time-harmonic electromagnetic wave problems with complex media* (Start: 10/2018)

9.2. International Initiatives

9.2.1. Inria International Partners

9.2.1.1. Informal International Partners

Wilkins Aquino (Duke University, USA)

Juan Pablo Borthagaray (University of Maryland, College Park, USA)

Fioralba Cakoni (University of Rutgers, USA)

Mahadevan Ganesh (Colorado School of Mines, USA)

Camille Carvalho (UC Merced, Merced, USA)

Christophe Geuzaine (Université de Liège, Belgium)

Bojan Guzina (University of Minnesota, USA)

Marcus Grote (Universitaet Basel, Switzerland)

Jean-François Molinari (EPFL, Lausanne, Switzerland)

Sergei Nazarov (Saint-Petersburg University, Russia)

Jerónimo Rodríguez (University of Santiago de Compostela, Spain)

Adrien Semin (TU Darmstadt, Germany)
Ricardo Weder (Universidad Nacional Autonoma, Mexico)
Shravan Veerapaneni (Univ. of Michigan at Ann Arbor, USA)
Jun Zou (Chinese University of Hong Kong, HK)

9.3. International Research Visitors

9.3.1. Visits of International Scientists

- Mahadevan Ganesh (Colorado School of Mines) – July 2018
- Bojan Guzina (University of Minnesota, USA) – Summer 2018, 1 month
- Michael Weinstein (Columbia University, USA) – May-June 2018
- Fedor Bakharev (Saint Petersburg State University, Russia) – July 2018

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Advisory and management activities

- E. Lunéville is the Head of UMA (Unité de Mathématiques Appliquées) at ENSTA ParisTech.
- P. Ciarlet is coordinator of the *Mathematics & Engineering Program* of the Mathematics Hadamard Labex (LMH)

10.1.2. Scientific events organisation end selection

- S. Chaillat co-organized with X. Claeys (LJLL, EPI ALPINES) the symposium of the International Association for Boundary Element Methods (IABEM), which took place in Paris in June 2018. They were about 140 attendees.
- A.-S. Bonnet-Ben Dhia co-organized a workshop entitled *“Advanced Theoretical and Numerical Methods for waves in structured Media”* in Paris in March 2018, in the framework of the GDR Ondes. They were about 90 attendees.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- A. S. Bonnet-Ben Dhia is an associate editor of SIAP *(SIAM Journal of Applied Mathematics)*.
- M. Bonnet is an associate editor of *Engineering Analysis with Boundary Elements*, *Journal of Optimization Theory* and *Application and Journal of Integral Equations and Applications*. He is in the editorial board of *Inverse Problems* and *Computational Mechanics*.
- P. Ciarlet is an editor of ESAIM:M2AN *(Mathematical Modeling and Numerical Analysis)*.
- P. Joly is a member of the Book Series Scientific Computing of Springer Verlag.

10.1.3.2. Reviewer - Reviewing Activities

The team members regularly review papers for many international journals.

10.2. Teaching - Supervision

10.2.1. Teaching

The permanent members of POEMS are involved in the engineering program at ENSTA ParisTech, the master program *"Analyse, Modélisation et Simulation"* (AMS) and the master program *"Modélisation et Simulation en Mécanique des Structures et Systèmes Couplés"* (MS2SC) of Université Paris-Saclay.

Eliane Bécache

- *Fonctions de variable complexe*, ENSTA (1st year)
- *La méthode des éléments finis*, ENSTA (2nd year) and Master AMS (M1)
- *Analyse et approximation par éléments finis d'EDP*, ENSTA (2nd year) and Master AMS (M1)
- *Résolution des problèmes de diffraction par équations intégrales*, ENSTA (3rd year), Master AMS (M2) and Master MS2SC (M2)

Marc Bonnet

- *Problème inverses et Identification*, Master MS2SC (M2)
- Co-head of the master program *"Modélisation et Simulation en Mécanique des Structures et Systèmes Couplés"* (MS2SC) of Université Paris-Saclay

Anne-Sophie Bonnet-Ben Dhia

- *Fonctions de variable complexe*, ENSTA (1st year)
- *Théorie spectrale des opérateurs autoadjoints*, ENSTA (2nd year) and Master AMS (M1)
- *Propagation et diffraction dans les guides d'ondes*, ENSTA (3rd year) and Master AMS (M2)
- *Non Destructive Testing*, Master "Acoustical Engineering" (M2)
- *Propagation des ondes élastiques dans les solides*, Master MS2SC (M2)

Laurent Bourgeois

- *Outils élémentaires pour l'analyse des équations aux dérivées partielles*, ENSTA (1st year)
- *Fonctions de variable complexe*, ENSTA (1st year)
- *Complétion de données et identification dans les problèmes gouvernés par des équations aux dérivées partielles*, ENSTA (3rd year) and Master AMS (M2)

Stéphanie Chaillat

- *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA (1st year)
- *Fonctions de variable complexe*, ENSTA (1st year)
- *La méthode des éléments finis*, ENSTA (2nd year) and Master AMS (M1)
- *Résolution des problèmes de diffraction par équations intégrales*, ENSTA (3rd year), Master AMS (M2) and Master MS2SC (M2)
- *Equations intégrales et multipôles rapides*, Ecole doctorale MODES (Univ. Paris Est, Marne la Vallée)

Colin Chambeyron

- *Remise à niveau en maths*, Licence (1st year), Paris-Dauphine University
- *Outils mathématiques*, Licence (L1), Paris-Dauphine University
- *Analyse - Optimisation*, Licence (L1), Paris-Dauphine University
- *Algèbre linéaire*, Licence (L2), Paris-Dauphine University

Patrick Ciarlet

- *Analyse et approximation par éléments finis d'EDP*, ENSTA (2nd year) and Master AMS (M1)
- *Préformation filière ModSim*, ENSTA (3rd year)
- *Calcul scientifique parallèle*, ENSTA (3rd year) and Master AMS (M2)
- *Modèles mathématiques et leur discrétisation en électromagnétisme*, ENSTA (3rd year) and Master AMS (M2)
- Deputy head of the master program *"Analyse, Modélisation et Simulation"* of Université Paris-Saclay

Sonia Fliss

- *La méthode des éléments finis*, ENSTA (2nd year) and Master AMS (M1)
- *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA (1st year)
- *Homogénéisation périodique*, ENSTA (3rd year), Master AMS(M2), Masters ANEDP, M4S
- *Propagation des ondes dans des milieux périodiques*, ENSTA (3rd year) and Master AMS (M2)

Laure Giovangigli

- *Calcul stochastique*, ENSTA (3rd year) and Master MMMEF (M2)

Christophe Hazard

- *Outils élémentaires d'analyse pour les équations aux dérivées partielles*, ENSTA (1st year)
- *Théorie spectrale des opérateurs autoadjoints*, ENSTA (2nd year) and Master AMS (M1)

Patrick Joly

- *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA (1st year)
- *Fonctions de variable complexe*, ENSTA (1st year)
- *Analyse fonctionnelle*, ENSTA (2nd year) and Master AMS (M2)
- *Propagation des ondes dans des milieux périodiques*, ENSTA (3rd year) and Master AMS (M2)

Maryna Kachanovska

- *Fonctions de variable complexe*, ENSTA (1st year)
- *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA (1st year)
- *Systèmes Dynamiques: Analyse et Stabilité*, ENSTA (1st year)

Nicolas Kielbasiewicz

- *Programmation scientifique en C++*, ENSTA (2nd year) and Master AMS (M1)
- *Projet de simulation numérique*, ENSTA (2nd year) and Master AMS (M1)
- *Calcul scientifique parallèle*, ENSTA (3rd year) and Master AMS (M2)

Eric Lunéville

- *Introduction au calcul scientifique*, ENSTA (2nd year).
- *Programmation scientifique en C++*, ENSTA (2nd year) and Master AMS (M1)
- *Projet de simulation numérique*, ENSTA (2nd year) and Master AMS (M1)
- *Propagation et diffraction dans les guides d'ondes*, ENSTA (3rd year) and Master AMS (M2)

Jean-François Mercier

- *Outils élémentaires d'analyse pour les équations aux dérivées partielles*, ENSTA (1st year)

- *Fonctions de variable complexe*, ENSTA (1st year)
- *Théorie spectrale des opérateurs autoadjoints*, ENSTA (2nd year) and Master AMS (M1)

Axel Modave

- *La méthode des éléments finis*, ENSTA (2nd year) and Master AMS (M1)
- *Calcul scientifique à haute performance*, ENSTA (2rd year) and Master AMS (M1)
- *Calcul scientifique parallèle*, ENSTA (3rd year) and Master AMS (M2)
- *Modèles mathématiques et leur discrétisation en électromagnétisme*, ENSTA (3rd year) and Master AMS (M2)

10.2.2. Supervision

PhD: Antoine Bensalah, *"Une approche nouvelle de la modélisation mathématique et numérique en aéroacoustique par les équations de Goldstein et applications en aéronautique"*, July 2018, Patrick Joly and Jean-François Mercier

PhD: Léandre Giret, *"Analyse numérique d'une méthode de décomposition de domaine non-conforme pour les équations SPN multigroupes"*, June 2018, Patrick Ciarlet and Erell Jamelot

PhD: Zouhair Adnani, *"Modélisation numérique tridimensionnelle de l'interaction sol-structure avec prise en compte des effets de site"*, May 2018, Marc Bonnet and Stéphanie Chaillat

PhD: Arnaud Recoquillay, *"Méthodes d'échantillonnage appliquées a l'imagerie de guides d'ondes élastiques"*, January 2018, Laurent Bourgeois

PhD in progress: Antoine Bera, *"Conception de perturbations invisibles pour les ondes électromagnétiques ou acoustiques"*, October 2016, Anne-Sophie Bonnet-Ben Dhia and Lucas Chesnel

PhD in progress: Sandrine Paolantoni, *"Analyse spectrale et simulation numérique de la diffraction électromagnétique par des métamatériaux"*, October 2016, Christophe Hazard and Boris Gralak

PhD in progress: Yohanes Tjandrawidjaja, *"Modélisation de la propagation d'ondes guidées et de leur interaction avec des défauts localisés dans une plaque élastique anisotrope pour des applications en SHM"*, October 2016, Anne-Sophie Bonnet-Ben Dhia and Sonia Fliss

PhD in progress: Emile Parolin, *"Non overlapping domain decomposition methods with non local transmission conditions for electromagnetic wave propagation"*, October 2017, Patrick Joly and Xavier Claeys

PhD in progress: Clément Beneteau, *"Asymptotic analysis of time harmonic Maxwell equations in presence of metamaterials"*, October 2017, Sonia Fliss and Xavier Claeys

PhD in progress: Hajer Methenni, *"Mathematical modelling and numerical method for the simulation of ultrasound structural health monitoring of composite plates"*, October 2017, Sonia Fliss and Sébastien Impériale

PhD in progress: Damien Mavaleix, *"Modeling of the fluid-structure interaction resulting from a remote underwater explosion"*, December 2017, Marc Bonnet and Stéphanie Chaillat

PhD in progress: Damien Chicaud, *"Méthodes de décomposition de domaine pour la résolution de problèmes harmoniques d'ondes électromagnétiques en milieux complexes"*, October 2018, Patrick Ciarlet and Axel Modave

PhD in progress: Mahran Rihani, *"Équations de Maxwell en présence de méta-matériaux"*, November 2018, Anne-Sophie Bonnet-Ben Dhia and Lucas Chesnel

PhD in progress: Yacine Abourrig, *"Boundary element method for modeling electromagnetic non-destructive testing: perturbative techniques for efficient and accurate parametric studies involving multiple simulations"*, October 2017, Marc Bonnet and Edouard Demaldent

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

- M. Kachanovska is a member of the *comité scientifique* of Inria-Saclay.
- A.-S. Bonnet-Ben Dhia is a member of the *bureau du comité des équipes-projets* (BCEP).

10.3.2. Interventions

- POEMS has been involved in the exhibition *"Rencontre diffractante"*, which has been presented successively at ENSTA *(from December 2017 to February 2018)* and at Inria *(in April and May 2018)*. The inspiring material of this exhibition was made up of numerical simulations of various diffraction problems studied within by POEMS team. They served as a basis for the creation of artistic objects made by several classes of the Ecole Boulle. *Curators of the exhibition : Jérôme Perez, ENSTA, and Virginie Gannac, doctor in art, design and applied arts from Université Paris I Sorbonne, Ecole Boulle de Paris*
- POEMS has been involved in the event *"Fête de la science"* at ENSTA-ParisTech in October 2018.
- E. Bécache presented a talk entitled *"Promenade mathématique"* during the day *"Filles et mathématiques, une équation lumineuse"* (March 27, 2018 at Ecole Polytechnique, Palaiseau) and during the awards ceremony of the National Olympiad of Mathematics (May 30, 2018 at Créteil).
- E. Bécache has been involved in a meeting of young female mathematics, organized on November 17-18, 2018 at ENSTA ParisTech.

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Publications of the year

Doctoral Dissertations and Habilitation Theses

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[2] A. RECOQUILLAY. *Sampling methods applied to Non Destructive Testing for elastic waveguides*, Université Paris-Saclay, January 2018, https://pastel.archives-ouvertes.fr/tel-01712219

Articles in International Peer-Reviewed Journals

[3] J. ALBELLA MARTÍNEZ, S. IMPERIALE, P. JOLY, J. RODRÍGUEZ. *Solving 2D linear isotropic elastodynamics by means of scalar potentials: a new challenge for finite elements*, in "Journal of Scientific Computing", 2018 [*DOI :* 10.1007/s10915-018-0768-9], https://hal.inria.fr/hal-01803536

[4] V. BARONIAN, L. BOURGEOIS, B. CHAPUIS, A. RECOQUILLAY. *Linear Sampling Method applied to Non Destructive Testing of an elastic waveguide: theory, numerics and experiments* , in "Inverse Problems", May 2018, https://hal.inria.fr/hal-01816810

[5] A. BENSALAH, P. JOLY, J.-F. MERCIER. *Well-posedness of a generalized time-harmonic transport equation for acoustics in flow*, in "Mathematical Methods in the Applied Sciences", May 2018, vol. 41, n^o 8, pp. 3117 - 3137 [*DOI :* 10.1002/MMA.4805], https://hal.inria.fr/hal-01897419

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[10] A.-S. BONNET-BEN DHIA, C. CARVALHO, P. CIARLET. *Mesh requirements for the finite element approximation of problems with sign-changing coefficients*, in "Numerische Mathematik", 2018, vol. 138, pp. 801-838 [*DOI :* 10.1007/S00211-017-0923-5], https://hal.archives-ouvertes.fr/hal-01335153

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[21] A.-S. BONNET-BEN DHIA, S. FLISS, Y. TJANDRAWIDJAJA. *Numerical analysis of the Half-Space Matching method with Robin traces on a convex polygonal scatterer*, in "Maxwell's equations", De Gruyter, 2018, https://hal.inria.fr/hal-01793511

Other Publications

[22] W. AQUINO, M. BONNET. *Analysis of the error in constitutive equation approach for time-harmonic elasticity imaging*, 2018, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01948668

[23] D. H. BAFFET, M. J. GROTE, S. IMPERIALE, M. KACHANOVSKA. *Energy Decay and Stability of a Perfectly Matched Layer For the Wave Equation*, September 2018, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01865484

[24] L. BARATCHART, S. CHEVILLARD, J. LEBLOND, E. A. LIMA, D. PONOMAREV. *Asymptotic method for estimating magnetic moments from field measurements on a planar grid*, 2018, working paper or preprint, https://hal.inria.fr/hal-01421157

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