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2020
ACTIVITY REPORT

Project-Team POEMS

Wave propagation: mathematical analysis and simulation

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

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Numerical schemes and simulations

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Project-Team POEMS

Creation of the Team: 2018 January 01, updated into Project-Team: 2019 November 01

Keywords

Computer sciences and digital sciences

A6. – Modeling, simulation and control

A6.1. – Methods in mathematical modeling

A6.1.1. – Continuous Modeling (PDE, ODE)

A6.1.2. – Stochastic Modeling

A6.1.4. – Multiscale modeling

A6.1.5. – Multiphysics modeling

A6.1.6. – Fractal Modeling

A6.2. – Scientific computing, Numerical Analysis & Optimization

A6.2.1. – Numerical analysis of PDE and ODE

A6.2.2. – Numerical probability

A6.2.3. – Probabilistic methods

A6.2.7. – High performance computing

A6.3.1. – Inverse problems

A6.3.4. – Model reduction

A6.5.1. – Solid mechanics

A6.5.2. – Fluid mechanics

A6.5.4. – Waves

Other research topics and application domains

B2.6. – Biological and medical imaging

B3.3. – Geosciences

B3.3.1. – Earth and subsoil

B3.4. – Risks

B3.4.1. – Natural risks

B3.4.2. – Industrial risks and waste

B5.3. – Nanotechnology

B5.4. – Microelectronics

B5.5. – Materials

1 Team members, visitors, external collaborators

Research Scientists

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- Eliane Bécache [Inria, Researcher, HDR]
- Stéphanie Chaillat [CNRS, Researcher, HDR]
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- Maryna Kachanovska [Inria, Researcher]
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- Laurent Bourgeois [École Nationale Supérieure de Techniques Avancées, Professor, HDR]
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- Laure Giovangigli [École Nationale Supérieure de Techniques Avancées, Associate Professor]
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Post-Doctoral Fellows

- Sara Touhami [École Nationale Supérieure de Techniques Avancées, from Jun 2020]
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PhD Students

- Amond Allouko [CEA, CIFRE, from Sep 2020]
- Pierre Amenoagbadji [École polytechnique, from Sep 2020]
- Laura Bagur [École Normale Supérieure de Paris, from Sep 2020]
- Clement Beneteau [École Nationale Supérieure de Techniques Avancées, until Aug 2020]
- Amandine Boucart [CEA]
- Damien Chicaud [École Nationale Supérieure de Techniques Avancées]
- Jean Francois Fritsch [CEA]
- Damien Mavaleix-Marchessoux [DCNS Group]
- Hajer Methenni [CEA]
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- Emile Parolin [Inria]
- Etienne Peillon [École Nationale Supérieure de Techniques Avancées, from October 2020]
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- Luis Alejandro Rosas Martinez [Inria, from Nov 2020]

Technical Staff

- Colin Chambeyron [CNRS, Engineer]
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Interns and Apprentices

- Amond Allouko [Inria, from Mar 2020 until Aug 2020]
- Pierre Amenoagbadji [Inria, from Mar 2020 until Sep 2020]
- Laura Bagur [ENSTA, From March until September 2020]
- Gregoire Corniere [Inria, from May 2020 until Aug 2020]
- Quingquing Hu [Inria, from Jun 2020 until Aug 2020]
- Quentin Krempp [Inria, from May 2020 until Jul 2020]
- Alberic Lefort [Inria, from May 2020 until Jul 2020]
- Alice Nassor [ENSTA, From March until September 2020]

Administrative Assistants

- Corinne Chen [École Nationale Supérieure de Techniques Avancées]
- Marie Enee [Inria]

Visiting Scientist

- Akram Beni Hamad [Université de Sousse - Tunisie, from Sep 2020]

External Collaborator

- Francis Collino [Collino, until Sep 2020]

2 Overall objectives

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.

3 Research program

3.1 Expertises

The activity of the team is oriented towards the design, the analysis and the numerical approximation of mathematical models for all types of problems involving wave propagation phenomena, in mechanics, physics and engineering sciences. Let us briefly describe our core business and current expertise, in order to clarify the new challenges that we want to address in the short and long terms.

Typically, our works are based on *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 scalar wave equation, or the Helmholtz equation if time-periodic solutions are considered. More generally, we systematically consider both the transient problem, in the time domain, and the time-harmonic problem, in the frequency domain. Let us mention that, even if different waves share a lot of common properties, the transition from the scalar acoustic equation to the vectorial electromagnetism and elastodynamics systems raises a lot of mathematical and numerical difficulties, and requires a specific expertise.

A notable particularity of the problems that we consider is that they are generally set in *unbounded domains*: for instance, for radar applications, it is necessary to simulate the interaction of the electromagnetic waves with the airplane only, without any complex environment perturbing the wave phenomena. This raises an intense research activity, both from a theoretical and a numerical point of view. There exist several approaches which all consist in rewriting the problem (or an approximation of it) in a bounded domain, the new formulation being well-suited for classical mathematical and numerical techniques.

One class of methods consists in applying an appropriate condition on some boundary enclosing the zone of interest. In the frequency domain, one can use a non-local transparent condition, which can be expressed by a convolution with a Green function like in integral equation techniques, or by a modal decomposition when a separation of variables is applicable. But for explicit schemes in the time domain, local radiation conditions at a finite distance are generally preferred (constructed as local approximations at various orders of the exact non-local condition). A second class of methods consists in surrounding the computational domain by so called *Perfectly Matched absorbing Layers* (PML), which are very popular because they are easy to implement. POEMS members have provided several contributions to these two classes of methods for more than twenty-five years. Among them, on can mention the understanding of the instability of PMLs in anisotropic media and in dispersive media, the derivation of transparent boundary conditions in periodic media or the improvement of Fast Multipole techniques for elastodynamic integral equations.

In addition to more classical domains of applied mathematics that we are led to use (variational analysis and functional analysis, interpolation and approximation theory, linear algebra of large systems, etc...), we have acquired a deep expertise in *spectral theory*. Indeed, the analysis of wave phenomena is intimately linked to the study of some associated spectral problems. Acoustic resonance frequencies of a cavity correspond to the eigenvalues of a selfadjoint Laplacian operator, modal solutions in a waveguide correspond to a spectral problem set in the cross section. In these two examples, if the cavity or the cross-section is unbounded, a part of the spectrum is a continuum. Again, POEMS has produced several contributions in this field. In particular, a large number of significant results have been obtained for the existence or non-existence of guided modes in open waveguides and of trapped modes in infinite domains.

To end this far from exhaustive presentation of our main expertise domains, let us mention the *asymptotic techniques* with respect to some small scale appearing in the model: it can be the wavelength compared to the size of the scatterer, or on the contrary, the scale of the scatterer compared to the wavelength, it can be the scale of some microstructure in a composite material or the width of a thin layer or a thin tube. In each case, the objective, in order to avoid the use of costly meshes, is to derive effective simplified models. Our specificity here is that we can combine skills in physics, mathematics and numerics: in particular, we take care of the mathematical properties of the effective model, which are used to ensure the robustness of the numerical method, and also to derive error estimates with respect to the small parameter. There has been a lot of contributions of POEMS to this topic, going from the modeling of electromagnetic coatings to the justification of models for piezoelectric sensors. Let us mention that effective models for small scatterers and thin coatings have been used to improve imaging techniques that we are developing (topological gradient, time reversal or sampling techniques).

3.2 New domains

In order to consider more and more challenging problems (involving non-deterministic, large-scale and more realistic models), we decided recently to enlarge our domain of expertise in three directions.

Firstly, we want to reinforce our activity on *efficient solvers for large-scale wave propagation problems*. Since its inception, POEMS has frequently contributed to the development and the analysis of numerical methods that permit the fast solution of large-scale problems, such as high-order finite element methods, boundary elements methods and domain decomposition methods. Nevertheless, implementing these methods in parallel programming environments and dealing with large-scale benchmarks have generally not been done by the team. We want to continue our activities on these methods and, in a more comprehensive approach, we will incorporate modern algebraic strategies and high-performance computing (HPC) aspects in our methodology. In collaboration with academic or industrial partners, we would like to address industrial-scale benchmarks to assess the performance of our approaches. We believe that taking all these aspects into consideration will allow us to design more efficient wave-specific computational tools for large-scale simulations.

Secondly, up to now, *probabilistic methods* were outside the expertise of POEMS team, restricting us to deterministic approaches for wave propagation problems. We however firmly believe in the importance and usefulness of addressing uncertainty and randomness inherent to many propagation phenomena. Randomness may occur in the description of complex propagation media (for example in the modeling of ultrasound waves in concrete for the simulation of non-destructive testing experiments) or of data uncertainties. To quantify the effect of such uncertainties on the design, behavior, performance or reliability of many systems is then a natural goal in diverse fields of application.

Thirdly and lastly, we wish to develop and strengthen collaborations allowing a *closer interaction between our mathematical, modeling and computing activities and physical experiments*, where the latter may either provide reality checks on existing models or strongly affect the choice of modeling assumptions. Within our typical domain of activities, we can mention four areas for which such considerations are highly relevant. One is musical acoustics, where POEMS has made several well-recognized contributions dealing with the simulation of musical instruments. Another area is inverse problems, whose very purpose is to extract useful information from actual measurements with the help of (propagation) models. This is a core of our partnership with CEA on ultrasonic Non Destructive Testing. A third area is the modelling of effective (acoustic or electromagnetic) metamaterials, where predictions based on homogenized models have to be confirmed by experiments. Finally, a fourth area of expertise is the modeling and simulations of waves in reactive media, where the development of simple mathematical models is of great importance in order to better understand the complex dynamics of reactive flows.

4 Application domains

Our research in wave-propagation finds applications in several different domains, ranging from understanding sound generation and propagation in aircrafts (aeroacoustics), to non destructive testing of industrial structures.

Nowadays, the numerical techniques for solving the basic academic problems are well mastered, and significant progress has been made during the last twenty years for handling problems closer to real applications. But several bottlenecks remain, among which one can mention the high-frequency problems for radar applications, the multiscale problems that arise for instance in nanotechnologies or the multi-physics couplings, like in *aeroacoustics*. Moreover, in the recent period, new challenges have emerged, related to new discoveries in physics (like negative index metamaterials) or to the fantastic development of information and communication techniques. For example, the growing development of increasingly connected objects (internet of things) and the forthcoming availability of autonomous vehicles depend crucially on electromagnetic waves, raising important issues about radar performance, sensor reliability, component miniaturization and electromagnetic compatibility. Generally, there are a lot of application domains which could benefit from advanced research on waves phenomena. Enhancing ultrasound-based methods for *detection* and *imaging*, which are already intensively used in e.g. medicine, could permit real-time health monitoring of aircrafts or nuclear plants. Guarding against seismic risks still requires considerable advances in the simulation of elastic waves in large and complex media. And many other applications motivating our research and our prospects could be added to this far-from-comprehensive list.

5 Highlights of the year

5.1 Highlights

- During the PhD of Damien Mavaleix-Marchessoux, in collaboration with Naval Group, we have demonstrated the capabilities of fast BEMs coupled with FEM to model underwater explosions, paving the way to the use of the technology at the production level. An important fact is to have proposed developments with various levels of maturity going from TRL1 (new fast BEMs in the time domain) to TRL6 (demonstration of the maturity of the software developed for the application considered).
- As a way to adapt to the sanitary situation, new teaching material was created by many members of the POEMS team for distance learning (tutorials, videos, ...).

6 New software and platforms

6.1 New software

6.1.1 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

6.1.2 XLiFE++

Keywords: Numerical simulations, Finite element modelling, Boundary element method

Functional Description: XLiFE++ is an FEM-BEM C++ library developed by POEMS laboratory and IRMAR laboratory, that can solve 1D/2D/3D, scalar/vector, transient/stationary/harmonic problems. Description: https://uma.ensta-paris.fr/soft/XLiFE++/

Contacts: Eric Lunéville, Nicolas Kielbasiewicz, Colin Chambeyron

7 New results

7.1 Modelling complex media

There is a need of a better understanding of wave phenomena in complex media. From a physical point of view, a *complex medium* is typically a material where the propagation of the waves may be *anisotropic* and *dispersive*, such as metamaterials with negative coefficients. These properties are generally the effect of a microstructure, that can be ordered (in e.g. photonic crystals), or disordered (ultrasounds in biological tissues, seismic waves). From a mathematical point of view, one can take into account exactly this microstructure or, at sufficiently low frequency, use effective models justified by the *homogenization theory*.

7.1.1 Ordered and disordered media

Transparent boundary conditions for periodic waveguides: analysis and extensions

Participants Sonia Fliss, Patrick Joly.

We consider the time harmonic scalar wave equation in junctions of several different periodic half-waveguides. In general this problem is not well posed. Several papers propose radiation conditions, i.e. the prescription of the behaviour of the solution at the infinities. This ensures uniqueness - except for a countable set of frequencies which correspond to the resonances- and yields existence when one is able to apply Fredholm alternative. This solution is called the outgoing solution. However, such radiation conditions are difficult to handle numerically. In this paper, we propose so-called transparent boundary conditions which enables us to characterize the outgoing solution. Moreover, the problem set in a bounded domain containing the junction with this transparent boundary conditions is of Fredholm type. These transparent boundary conditions are based on Dirichlet-to-Neumann operators whose construction is described in the paper. On contrary to the other approaches, the advantage of this approach is that a numerical method can be naturally derived in order to compute the outgoing solution. Numerical results illustrate and validate the method. This work is done in collaboration with Vincent Lescarret (LSS, Centrale Supélec).

Guided modes in a hexagonal periodic graph-like domain: the zigzag and the armchair cases

Participants Sonia Fliss.

In this work, done in collaboration with Bérangère Delourme (LAGA, Paris 13), we study the wave propagation in hexagonal periodic media that are close to a graph domain. By using an asymptotic analysis, we exhibit situations where the introduction of lineic defects into the geometry of the domain leads to the appearance of guided modes and we show that the direction of the defect leads to very different properties of the guided modes.

Wave propagation in quasi periodic media

Participants Sonia Fliss, Patrick Joly, Pierre Amenoagbadji.

A quasi-periodic medium is an ordered medium without being periodic. A fairly well-known example since the 2011 Nobel Prize in Chemistry is the quasi-crystal. The notion of quasi-periodic and more generally almost periodic function is a very well defined notion in mathematical literature (see in particular the books by Besikovitch and Bohr). To give an idea, a 1D quasi-periodic function of order N is a cut in a non-rational direction of a periodic function of N variables. PDEs with quasi-periodic coefficients have been the subject of a number of theoretical studies (see in particular the work of RM Levitan, VV Zhikov) but it seems that apart in the context of homogenization, there has been much less work on the numerical resolution of these equations.

The objective of this work is to develop original numerical methods for the solution of the time-harmonic wave equation in quasi-periodic media, in the spirit of the methods that we have developed previously for periodic media. The idea is to use, as in the work of Gerard-Varet and Masmoudi, that the study of an elliptic PDE (in the sense that the principal part of the operator is elliptic) with quasi-periodic coefficients comes down to the study of a non-elliptic PDE in higher dimension but whose coefficients are periodic. The periodic nature of the coefficients allows us to use of specific tools adapted for periodic media. However the non-elliptic nature of the equation makes the mathematical and numerical analysis of the PDE difficult.

For now, we have considered the Helmholtz equation, with a not-real frequency, in one dimensional quasi periodic media of order 2. Using the idea explained above, to solve this problem, it suffices to solve a non elliptic PDE with periodic coefficients set in a band with periodic boundary conditions. Our method to solve the Helmholtz equation in periodic waveguides can be extended to the non-elliptic case. The associated numerical method has been already implemented. When the frequency is real, the theoretical justification is less clear even if from a numerical point of view, the method works well.

Wave equation in a weakly randomly perturbed periodic medium

Participants Sonia Fliss, Laure Giovangigli.

In this work we consider the solution of the time harmonic wave equation in a one dimensional periodic medium with weak random perturbations. More precisely, we study two types of weak perturbations: (1) the case of stationary, ergodic and oscillating coefficients, the typical size of the oscillations being small compared to the wavelength and (2) the case of rare random perturbations of the medium, where each period has a small probability to have its coefficients modified, independently of the other periods. Our goal is to derive an asymptotic approximation of the solution with respect to the small parameter. This can be used in order to construct absorbing boundary conditions for such media.

7.1.2 Derivation of effective models

Enriched homogenized model in the presence of boundaries for wave equations

Participants Clément Bénéteau, Sonia Fliss.

We study the wave equation in presence of a periodic medium when the period is small compared to the wavelength. The classical homogenization theory enables to derive an effective model which provides an approximation of the solution. However, it is well known that these models are not accurate near the boundaries. In this work, we propose an enriched asymptotic expansion which enables to derive high order effective models at any order, when the geometry of the periodic medium is simple — absence of corners and its boundary (or the interface with other media) must lie in a direction of periodicity. For the model at order 1, the volume equation is the same than the classical one, but the boundary/transmission conditions is modified. Let us mention that the model of order 2 is particularly relevant when one is interested in the long time behaviour of the solution of the time-dependent wave equation. Indeed, it is well-known that the classical homogenized model does not capture the long time dispersion of the exact solution. In several works, homogenized models involving differential operators of high order (at least 4), are proposed for the wave equation in infinite domains. Dealing with boundaries and proposing boundary conditions for these models were open questions. Our approach enables to propose appropriate and accurate boundary conditions for these models. The analysis of such model and its implementation is under investigation. This work is the fruit of a long time collaboration with Xavier Claeys (LJLL, Sorbonne University) and a recent one with Timothée Pouchon (EPFL). Clement Beneteau has defended his PhD thesis in January 2021.

Homogenization of resonant or non-resonant thin scatterers arrays

Participants Jean-François Mercier.

In collaboration with Agnès Maurel (Langevin Institut) and Kim Pham (IMSIA), we developp interface effective models to describe acoustics propagation through thin scatterers arrays. Such effective models involve jump conditions for the fields whose interface parameters are determined thanks to matched asymptotic expansions. We have done non-resonant and resonant homogenization:

- Perfect Brewster transmission through ultrathin perforated films :

  For a plane acoustic wave at oblique incidence on a perforated film, sound penetrable or rigid, we determine the Brewster incidence realizing a perfect transmission. For thick films, the classical volume homogenization provides an accurate prediction of the Brewster angle. However, for thinner films, it deviates from the volumetric prediction. To properly describe this shift, an interface model is built. When varying the contrasts in the material properties of the film and of the surrounding matrix, the model is found to accurately reproduce the spectra of perforated films, from ultrathin to relatively thick.

- Effective transmission conditions across a resonant bubbly metascreen :

  The extension to resonant obstacles has been considered with the study of the acoustic propagation through a thin bubbly screen. The analysis is conducted in the time domain and a difficulty is to preserve the non-linear response of the bubbles in the equivalent interface model. We have been able to provide an effective model involving a jump of the normal velocity coupled to a non-linear equation of the Rayleigh-Plesset's type for the bubble radius.

Mathematical modelling of thin coaxial cables

Participants Patrick Joly, Akram Beni Hamad.

This topic is the subject of a long term collaboration with Sébastien Imperiale (M3disim).

The numerical simulation of the time domain propagation of electromagnetic waves in networks of coaxial electric cables is an important issue in many industrial applications which also represents a scientific challenge given the very different scales present in the problem, in particular the small tranverse dimensions of the cables. Using a direct approach via 3D Maxwell's equations in 3 dimensions would be quite expensive if not out of reach. This is why it is natural to seek to offer approximate mono-dimensional models which was the subject of the previous PhD thesis of G. Beck. Such models can be derived from an asymptotic analysis of 3D Maxwell's equatiosn and must handle complex situations, including the highly heterogeneous nature of the internal structure of electric cables as well as geometry imperfections, and junctions of cables.

One of the last theoretical contributions has been concerned with loss phenomena due to skin effects and gave rise to an article to appear in SN Partial Differential Equations and Applications. The effective model involves a fractional time derivatives that ac- counts for the skin effects.

All of these models have been rigorously justified from a mathematical point of view in Geoffrey Beck's thesis, the truly operational phase of the work, especially everything related to real applications, remained to be done. This is the object of the PhD thesis of Akram Beni Hamad, which started in 2018 that pursues a triple goal :

1. Propose, analyze and implement effective numerical methods for solving the 1D approximate problems.

2. Quantify the errors induced by approximate models, and consequently identify the limits of validity, through the comparison between 1D and 3D simulations.

3. In order to achieve the goal 2, design numerical methods for solving Maxwell 3D equations dedicated to taking into account the specificity of thin electric cables.

This last point led us to propose an original approach consisting in adapting Nédélec's edge elements to elongated prismatic meshes and proposing a hybrid time discretization procedure which is explicit in the longitudinal directions and implicit in the transverse dimensions. On particular, the resulting CFL stability condition is not affected by the smallness of the width of the cable. The first obtained numerical results are quite promising.

Stability and Accuracy of the Time-Domain Foldy-Lax Model

Participants Maryna Kachanovska.

This work is a collaboration with Maxence Cassier (Institut Fresnel, Marseille). The Foldy-Lax model is an asymptotic model used to compute the solution to the problem of scattering by small obstacles in the frequency domain. Our numerical experiments indicate that this model can be used as well in the time domain. The theoretical justification of its stability and convergence is based on a very simple idea, namely the use classical in the Time-Domain Boundary Integral Equations community Laplace domain techniques. We prove in particular that the Foldy-Lax method is nothing else but the Galerkin discretization of the single-layer boundary integral equation, with specially chosen basis functions, in which the discretization matrix is further approximated. The error estimates then rely on the Céa's lemma. We are currently working on the proof of the stability of the problem (the difficulty comes from the approximation of the discretization matrix).

Modelling a thin layer of randomly distributed nano-particles

Participants Sonia Fliss, Laure Giovangigli, Amandine Boucart.

This is a joint work with Bruno Stupfel from CEA-DAM. We study the scattering of a plane wave by a heterogeneous object covered with a thin layer of randomly distributed nano-particles. The size of the particles, their distance within each others and the thickness of the layer are of the same order, and small compared to the wavelength of the incoming wave. Solving numerically Maxwell's equations with finite elements techniques in this context is very costly. To circumvent this, we propose an effective model where the layer of the particles is replaced by an equivalent boundary condition. Under certain assumptions on the random distribution of the particles, we obtain this model via a multi-scale asymptotic expansion of the solution with respect to the small size of a particle. The coefficients that appear in the equivalent boundary condition are computed from so-called cell problems defined on an unbounded domain. We approximate these problems by periodic cell-problems solved on a large period.

Propagation of ultrasounds in complex biological media

Participants Laure Giovangigli.

This is a joint work with Pierre Millien from Institut Langevin. The project aims at modelling and studying the propagation and diffusion of ultrasounds in complex biological media in order to obtain quantitative images of physical parameters of these media.

The propagation of ultrasounds in biological tissues is a complex multi-scale phenomenon: the scattered wave is produced by small (compared to the wavelength) inhomogeneities randomly distributed throughout the media, but the time of flight is affected by the slow (compared to the wavelength) variations of the medium.

In order to capture both of those effects, we model the biological tissue as a slowly varying medium described by smooth coefficients in which lie small scatterers that are randomly distributed throughout the medium. Under certain assumptions on this distribution, we perform an asymptotic expansion of the scattered wave with respect to the size of the inclusions via stochastic homogenization techniques. Grégoire Cornière, a second year student at ENSTA Paris, studied this model during his research internship in spring and summer 2020 and verified numerically the convergence of the exact solution to its asymptotic expansion in the case where the background medium has constant density and bulk modulus.

Weakly non-linear waves in reactive media

Participants Luiz Faria.

Understanding waves in a reactive media is a challenging task due to the intricate coupling between the fluid dynamical equations and the chemical reactions. While the reactive compressible Navier-Stokes equations can be used to simulate such flows, their complexity make it very difficult to understand them both mathematically and physically. For this reason, simplified (asymptotic) models of reactive waves have been an important area of research in the field of combustion for decades. One of the most challenging phenomena in combustion is the deflagration-to-detonation transition (DDT), where a slow diffusion-driven wave can spontaneously accelerate into a supersonic shock wave under some conditions. In collaboration with researchers at the Institute Pprime in Poitier, we have recently proposed a new simplified model for DDT in narrow channels. This is a combined experimental and theoretical work. In particular, some distinguishing features characterizing the late stages of DDT are shown to be qualitatively captured by a simple one-dimensional scalar equation. Inspection of the structure and stability of the traveling wave solutions found in the model, and comparison with experimental observations, suggest a possible mechanism responsible for front acceleration and transition to detonation [24].

7.1.3 Analysis of effective models

Analysis of variational formulations and low-regularity solutions for time-harmonic electromagnetic problems in complex anisotropic media

Participants Chicaud Damien, Ciarlet Patrick, Modave Axel.

In this work, we have considered the time-harmonic Maxwell's equations with physical parameters, namely the electric permittivity and the magnetic permeability, that are complex, possibly non-hermitian, tensor fields. Both tensor fields verify a general ellipticity condition. We have proven the well-posedness of formulations for the Dirichlet and Neumann problems (*i.e.* with a boundary condition on the electric field or its curl, respectively) using well-suited functional spaces and Helmholtz decompositions. For both problems, the *a priori* regularity of the solution and the solution's curl has been analysed. The regularity results have been obtained by splitting the fields and using shift theorems for second-order divergence elliptic operators. Finally, we have considered the discretization of the formulations with a $\mathbf{H}(\mathbf{curl})$-conforming approximation based on edge finite elements. An a priori error estimate has been derived and verified thanks to numerical results with an elementary benchmark.

Mathematical analysis of metamaterials in time domain

Participants Christophe Hazard, Patrick Joly, Alex Rosas Martinez.

This topic is the subject of our important collaboration with Maxence Cassier (Institut Fresnel).

An important effort has been devoted to the writing of a long paper (60 pages) on the limiting absorption and limiting amplitude (understand long time behaviour) principles for the transmission problem between two half-spaces, one made of vacuum and the other filled by a Drude material. This is the second part of a work whose first part, devoted to the spectral theory of the problem, was published in Communications in PDEs (where the second part will be submitted too). The approach is based on the use of so-called stationary scattering method that must be adapted to the specificities of the constitutive laws of Drude media, specificities that are also the source of new phenomena such as plasmonic interface waves or interface resonances.

The continuation of the above work is the object of the PhD thesis of Alex Rosas Martinez who started last November. We are working on more general dispersive and passive materials (Drude materials are one example) and try to understand the role of the structure of the measure involved in the Herglotz-Nevanlinna representation of the frequency dependent permittivity and permeability of these media on the apparition of dissipative effects : the conjecture is that these are due to the existence of an absolutely continuous part (with respect to Lebesgue's measure).

Essential spectrum related to an interface with a negative material

Participants Christophe Hazard, Sandrine Paolantoni.

The studies carried out in recent years about the spectral effects of an interface between vacuum and a negative material (that is, a dispersive material whose electric permittivity and/or magnetic permeability become negative in some frequency range) come to an end with the defense of the PhD thesis of Sandrine Paolantoni. During this last year, we have on the one hand extended the previous results obtained for a polygonal interface to the case of a smooth curved boundary (which leads to far more involved technical calculations). On the other hand, we have explored more deeply the difficulties which appear in the numerical approximation of the spectrum, in particular the dispersion of the numerical spectrum which can be avoided thanks to a suitable choice of the mesh (local symmetry of the mesh with respect to the interface).

Computation of plasmon resonances localized at corners using frequency-dependent complex scaling

Participants Anne-Sophie Bonnet-Ben Dhia, Christophe Hazard, Florian Monteghetti.

A smooth metallic particle supports surface plasmonic modes for a discrete sequence of negative permittivity values. For a subwavelenth particle, in the quasi-static approximation, these values are solution of the so-called plasmonic eigenvalue problem. This work investigates the case where the particle has corners. It is well-known that a metallic particle with a non-smooth boundary can exhibit, in some range of permittivity values, strongly-oscillating surface waves whose phase velocities vanish as they reach the corners. This range of permittivity corresponds to the essential spectrum of the former spectral problem.

We are interested by the existence of corner resonances, which are analogous to scattering resonances in the sense that the local behavior at each corner plays the role of the behavior at infinity. Resonant values of the permittivities are sought as eigenvalues of the plasmonic eigenvalue problem with an appropriate complex scaling applied at the corners. The finite element discretization requires a very specific mesh in the vicinity of the surface of the particle, to avoid spurious eigenvalues. Numerical results obtained for an elliptic particle with one corner show that the complex scaling deforms the essential spectrum (associated with the corner) so as to unveil both embedded plasmonic eigenvalues and complex plasmonic resonances.

Maxwell's equations in presence of a conical tip with negative electromagnetic constants

Participants Anne-Sophie Bonnet-Ben Dhia, Mahran Rihani.

This work is done in collaboration with Lucas Chesnel from CMAP at Ecole Polytechnique. We are interested in the analysis of time-harmonic Maxwell's equations in presence of a conical tip of a material with negative dielectric constants. When these constants belong to some critical range, the electromagnetic field exhibits strongly oscillating singularities at the tip which have infinite energy. In the 2D case of a wedge with critical electromagnetic constants, it has been proved for the equivalent scalar problems that well-posedness in the classical H^1 framework is lost. Well-posedness can be recovered (in a non standard framework) by working in weighted Sobolev spaces and adding in the space the outgoing propagating singularity. We have shown how to provide such functional framework for 3D Maxwell's equations, when the dielectric permittivity and/or the magnetic permeability take critical values [39].

Towards non-local interface models

Participants Patrick Ciarlet.

Collaboration with Juan Pablo Borthagaray (DMEL, Universidad de la República, Salto, Uruguay). Consider the equation $\mathrm{div}(\sigma\nabla u) = f$ in Ω (plus boundary conditions), where the diffusivity is piecewise constant, and equals σ_i in Ω_i $(i = \{1,2\})$, with $\overline{\Omega_1} \cup \overline{\Omega_2} = \overline{\Omega}$ and $\Omega_1 \cap \Omega_2 = \emptyset$. If σ_1 and σ_2 have different sign, well-posedness in $H^1(\Omega)$ may not hold. This occurs when the ratio σ_2/σ_1 belongs to the so-called *critical interval*. When the interface has a corner, we have observed that this critical interval is shrunk if one replaces the standard H^1-bilinear forms by corresponding H^s-forms ($s \in (0,1)$). However, the expense of computing the nonlocal interactions may be prohibitive in applications. Thus, our long term goal is to confine the non-local model to a neighborhood of the interface, while keeping the standard local model in the rest of the domain. A first step in this direction consists in considering the numerical solution of the fractional Laplacian of index $s \in (1/2,1)$ in a bounded domain Ω with homogeneous Dirichlet boundary conditions. Its solution a priori belongs to the fractional order Sobolev space $\widetilde{H}^s(\Omega)$. Under suitable assumptions on the data, 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 $H^1(\Omega)$. We show how to derive error estimates for the Lagrange finite element solutions on both quasi-uniform and graded meshes.

Wave Propagation in Hyperbolic Metamaterials

Participants Patrick Ciarlet, Maryna Kachanovska, Etienne Peillon.

The hyperbolic metamaterials are metamaterials which behave like metals in one direction of wave propagation and like dielectric in another one. Unlike isotropic metamaterials, they exist in nature; a typical example is a cold plasma. Wave propagation in cold strongly magnetized plasmas is described by the Maxwell's equations with a diagonal tensor of dielectric permittivity with entries of different signs, i.e. the problem becomes close to hyperbolic. The main idea is to obtain the radiation condition in an explicit form, by not resorting to the Fourier analysis techniques. We have obtained a weighted radiation condition for the solution, with the weight degenerating at the characteristics. it remains to prove the uniqueness with this radiation condition. We are exploring the related techniques, such as extension of the Morawetz multipliers in the hyperbolic case.

7.2 Efficient methods for direct and inverse problems

Numerical methods for wave problems have to deal with two particular difficulties. The first one is the fact that scattering problems are generally posed in unbounded domains. Depending on the complexity of the background, different approaches can be used to formulate them in a bounded domain, suitable for a discretization. Secondly, when the wavelength is very small in comparison to a characteristic length of the scatterer, the linear system resulting from the discretization may be very large and new strategies are needed to reduce the complexity and speed up the resolution. Fast solvers of the direct problem are useful for inverse problems or shape optimization, when iterative procedures are used. An alternative lies in the use of sampling methods, which do not require a priori knowledge of the imaged defect. Also asymptotic approximations for small defects can be exploited.

7.2.1 Transparent and absorbing boundary conditions

An automatic PML for acoustic finite element simulations in convex domains of general shape

Participants Modave Axel.

In collaboration with Hadrien Bériot from Siemens Industry Software N.V. (Leuven, Belgium), we have addressed the efficient finite element solution of exterior acoustic problems with truncated computational domains surrounded by perfectly matched layers (PMLs). The PML is a popular non-reflecting technique, which combines accuracy, computational efficiency and geometric flexibility. Unfortunately, the effective implementation of the PML for generally-shaped convex domains is tricky because of the geometric parameters that are required to define the PML medium. In this work, a comprehensive implementation strategy has been proposed. This approach, which we called the automatically matched layer (AML) implementation, is versatile and fully automatic for the end-user. With the AML approach, the mesh of the layer is extruded, the required geometric parameters are automatically obtained during the extrusion step, and the effective implementation relies on a simple modification of the Jacobian matrix in the element-wise integrals. The AML implementation has been validated and compared to other implementation strategies using numerical benchmarks in two and three dimensions, considering computational domains with regular and non-regular boundaries. A three-dimensional application with a generally-shaped domain generated using a convex hull has been proposed to illustrate the interest of the AML approach for realistic industrial cases.

Stability and Convergence of Perfectly Matched Layers in Waveguides

Participants Eliane Bécache, Maryna Kachanovska.

This work is dedicated to the proof of stability and convergence of the Bérenger's perfectly matched layers in the waveguides for an arbitrary L^∞ damping function. The proof relies on the Laplace domain techniques and an explicit representation of the solution to the PML problem in the waveguide. A bound for the PML error that depends on the absorption parameter and the length of the PML is presented. Numerical experiments confirm the theoretical findings.

Stability and Convergence of Perfectly Matched Layers in Dispersive Waveguides

Participants Eliane Bécache, Maryna Kachanovska, Markus Wess.

This work is a post-doctoral research project of Markus Wess. The aim is to analyze the stability and convergence of the generalized perfectly matched layers for dispersive media, proposed by Bécache, Joly, Vinoles. The idea is to extend the techniques for non-dispersive media to the dispersive case. Like in the non-dispersive case, we obtain an explicit representation of the solution in the Laplace domain; it remains to estimate the inverse Laplace integral. One of the difficulties compared to the non-dispersive case is the appearance of various propagation regimes (also in the time domain): there exist backward propagating waves, forward propagating waves, evanescent waves depending on the frequency. This is expressed in the complexity of the expression which needs to be estimated. We have exploited the possibility of obtaining semi-explicit expressions (by using the residues theorems, or Laplace transforms of Bessel functions), and currently are studying the idea of deforming the contour in the complex plane which would minimize the value of the integrand.

The complex-scaled Halfspace Matching Method

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

We developed for some years a method that we call the Half-Space Matching (HSM) method, to solve scattering problems in unbounded domains, when classical approaches are either not applicable or too expensive. This method is based on an explicit expression of the "outgoing" solution of the problem in half-spaces, by using Fourier, generalized Fourier or Floquet transforms when the background is respectively homogeneous (possibly anisotropic), stratified or periodic. The domain exterior to a bounded region enclosing the scatterers is recovered by a finite number of halfspaces (at least 3). The unknowns of the formulation are the restriction of the solution to the bounded region and the traces of the solution on the infinite boundaries of the halfspaces. The system of equations is derived by writing compatibility conditions between the different representations of the solution. Although the HSM method works in the non-dissipative case, the theoretical and the numerical analysis of the method has been done only in the dissipative case. In the present work done in collaboration with Simon Chandler-Wilde and Karl-Michaël Perfekt form Reading University, we propose a new formulation of the method which is well-suited for the theoretical and numerical analysis of the non dissipative case. In the spirit of PMLs, the idea is to replace the system of equations on the traces by similar equations on exponentially decaying analytical extensions of the traces. In the simple case of the Helmholtz equation, we have proved that this formulation is of Fredholm type and is well-posed. Besides the interest for the theory, this new formulation is also well-suited for numerical purposes. Indeed one can show that the error due to the truncation of the infinite boundaries of the half-spaces decays exponentially with the distance of truncation, which was not the case for the standard method. The analysis requires the study of double-layer potential integral operators on intersecting infinite lines, and their analytic continuations. The effectiveness of the method is validated by preliminary numerical results.

The Half-Space Matching method for evolution problems

Participants Sonia Fliss, Hajer Methenni.

The motivation of this work is the resolution of elastodynamic equations in anisotropic unbounded media with localized perturbations. All the classical methods to restrict the computation around the perturbations are unstable in anisotropic elastic media (PML for instance) or really costly (Integral equations). The idea is to extend to the time domain the Halfspace Matching (HsM) method which is already developed for time-harmonic problems. In order to propose a stable discretization, we first semi-discretize in time the problem with a stable scheme. Two different approaches can then be used. Let us describe them for an exterior problem . The first one consists in applying the Halfspace Matching Method to the semi-discrete problem, the unknowns being the traces of the solution on infinite lines. One has to solve at each time step a system of integral equations whose right hand side is a discrete convolution involving the traces at the previous tome steps. The second one consists in applying the Z transform —as in the convolution quadrature method— and apply the Halfspace Matching Method to a large number of independent frequency domain problems. The two approaches were implemented using

Xlife++ and compared. This work is done in collaboration with Sebastien Imperiale (Inria EPI M3DISIM) and Alexandre Imperiale (CEA-LIST).

Evaluation of oscillatory integrals in the Halfspace Matching Method

Participants Amond Allouko, Anne-Sophie Bonnet-Ben Dhia, Sonia Fliss.

This work concerns the Half Space Matching method described just above. A main ingredient of this method is a half-space formula for the outgoing scattered field, as a function of its trace on the boundary of the half-space. For homogeneous isotropic or anisotropic backgrounds, this formula is obtained thanks to a partial Fourier transform and gives raise to oscillatory integrals, hard to compute with standard quadrature formulas. We proposed two ways for improving both the accuracy and the efficiency of the evaluation of this half-space formula. When it is evaluated at a point located far enough from the boundary of the half-space, a simple far-field formula can be used. For other points, a deformation of the Fourier path in the complex plane allows to get rid of the oscillations and of the singularity at the branch point. Numerical experiments for the simple 2D isotropic case confirm that these two ideas drammatically reduce the cost of the method.

PML-BIE methods for unbounded interfaces

Participants Sonia Fliss, Anne-Sophie Bonnet-Ben Dhia, Luiz Faria, Stéphanie Chaillat.

In order to handle infinite interfaces in a boundary integral equation context, a few options are available. For simple geometries, one can construct a problem specific Greens function which incorporates the imposed boundary condition on all but a bounded portion of the interface, thus reducing the problem again to integrals over bounded curves/surfaces. This has the advantage of being conceptually simple provided such problem-specific Greens function can be efficiently computed. Unfortunately, for all but the simplest geometries, the representation of the problem specific Greens function involves challenging integrals which must be approximated numerically. An alternative approach consists of utilizing the free-space Greens function — readily available for many PDEs of physical relevance — in conjunction with a truncation technique. For non-dissipative problems, the slow (algebraic) decay of the Greens function makes the choice of truncation technique an important aspect which needs to be considered in order to reduce the errors associated with the domain's truncation.

Our objective in this project is to develop an extension of the method of perfectly-matched-layers (PMLs) to boundary integral equations. Building on previous works which consider the application of PMLs to two dimensional Helmholtz equation, the plan is to extend the methodology to consider other PDEs, as well as non-orthogonal PMLs. Such an extension has some important practical consequences, as it allows for the solution to be reconstructed on a much larger domain at the same computational cost, thus enabling in particular for a partial reconstruction of the far field using solely the free-space Greens function.

7.2.2 Accelerated solvers for large scale problems

Non-overlapping Domain Decomposition Method (DDM) using non-local transmission operators for wave propagation problems.

Participants Patrick Joly, Emile Parolin.

The research in this direction was mainly concerned by the extension to the electromagnetic setting of the linear convergence theory of non-overlapping DDM that relies on non-local transmission operators. The principal task was to propose, analyse and implement some candidate non-local operators satisfying the assumptions of the theory. There were two main propositions:

- Integral operator for the electromagnetic setting: the operator is available in closed form and its structure lead naturally to a localizable form via truncation of the kernel to limit the effective computational cost while retaining its good properties. The construction of such an operator turned out to be somewhat difficult due to the particular functional setting of Maxwell's equations.
- DtN based non-local operator: the operator is computed by solving auxiliary coercive problems in the vicinity of the transmission interface. The computational cost remains moderate as the implementation no longer involve dense matrix blocks from the integral operators but rather lead to augmented sparse linear systems. Initially developed for the electromagnetic setting, the approach is appealing as it provided a unified formalism that can be applied both to Helmholtz and Maxwell equations and proved to be efficient in numerical experiments.

Another important research direction is created by the technical and theoretical difficulty posed by junction points, which are points where three or more sub-domains abut. Xavier Claeys recently proposed a method to deal with this specific issue, based on the multi-trace formalism, which led to a joint collaboration on the subject. The main idea is to perform a global exchange operation, on the whole skeleton, rather than a local point-to-point exchange. The preliminary numerical results recently obtained are promising.

General-purpose kernel regularization of boundary integral equations via density interpolation

Participants Luiz Faria, Marc Bonnet.

This research is done in collaboration with Carlos Pérez-Arancibia (PUC, Chile).

We develop a general high-order kernel regularization technique applicable to all four integral operators of Calderón calculus associated with linear elliptic PDEs in two and three spatial dimensions. The proposed technique relies on interpolating the density function around the kernel singularity in terms of solutions of the underlying homogeneous PDE, so as to recast singular and nearly singular integrals in terms of bounded (or more regular) integrands. We developed a simple interpolation strategy which, unlike previous approaches, does not entail explicit computation of high-order derivatives of the density function along the surface. Furthermore, the proposed approach is kernel- and dimension-independent in the sense that the sought density interpolant is constructed as a linear combination of point-source fields, given by the same Green's function used in the integral equation formulation, thus making the procedure applicable, in principle, to any PDE with known Green's function. In the initial work [22], we have focused on Nyström methods for the (scalar) Laplace and Helmholtz equations and the (vector) elastostatic and time-harmonic elastodynamic equations. The method's accuracy, flexibility, efficiency, and compatibility with fast solvers was demonstrated by means of a variety of large-scale three-dimensional numerical examples.

Planewave Density Interpolation Methods for the EFIE on Simple and Composite Surfaces

Participants Luiz Faria.

Work done in collaboration with Catalin Turc (NJIT, USA), Costis Sideris (USC, USA), and Carlos Pérez-Arancibia (PUC, Chile).

This research presents an extension of the planewave density interpolation method to the electric-field integral equation (EFIE) for problems of scattering and radiation by perfect electric conducting objects. Relying on the Kirchhoff integral formula and local interpolations of the surface currents that regularize the kernel singularities, the technique enables off- and on-surface EFIE operators to be reexpressed in terms of integrands that are globally bounded over the domain of integration, regardless of the magnitude of the distance between the target and source points. Surface integrals resulting from the application of the method of moments using the Rao–Wilton–Glisson basis functions can then be directly evaluated by means of elementary quadrature rules irrespective of the singularity location. The proposed technique can be applied to simple and composite surfaces comprising two or more overlapping components. The use of composite surfaces can significantly simplify the geometric treatment of complex structures, as the density interpolation method enables the use of separate nonconformal meshes for the discretization of each of the surface components that make up the composite surface. Three-dimensional examples including multiscale and intricate structures were considered in order to validate the method.

Convolution quadrature based boundary integral equations for transient fluid-structure interaction

Participants Marc Bonnet, Stéphanie Chaillat, Damien Mavaleix-Marchessoux, Alice Nassor.

This study is done in collaboration with Bruno Leblé (Naval Group). It aims at developing computational strategies for modelling the impact of a far-field underwater explosion shock wave on a structure, in deep water. An iterative fluid-structure coupling is developed to solve the problem. Two complementary methods are used: the Finite Element Method (FEM), that offers a wide range of tools to compute the structure response; and the Boundary Element Method (BEM), more suitable to deal with large surrounding fluid domains. We concentrate on developing (i) a fast transient BEM procedure and (ii) a transient FEM-BEM coupling algorithm. The fast transient BEM is based on a fast multipole-accelerated Laplace-domain BEM (implemented in the in-house code COFFEE), extended to the time domain by the Convolution Quadrature Method (CQM). In particular, using empirical approximations for the solution of integral problems involving large (complex) frequencies has been found to yield satisfactorily accurate solutions while saving significant amounts of computational work. We currently focus on the development, proof of convergence and implementation of global-in-time iterative solution procedures for the coupled transient fluid-structure problem.

Modelling the sound radiated by a turbulent flow

Participants Stéphanie Chaillat, Jean-François Mercier, Nicolas Trafny.

This study is done in collaboration with Gilles Serre (Naval Group) and Benjamin Cotté (IMSIA). The aim is to develop an optimized method to determine numerically the 3D Green's function of the Helmholtz equation in presence of an obstacle of arbitrary shape, satisfying the Neumann boundary condition at the boundary surfaces. This so-called rigid Green's function is useful to solve the Lighthill's equation, giving the hydrodynamic noise radiated by a ship. First an integral equation is derived, expressing the rigid Green's function versus the free space Green's function. Then a Boundary Element Method (BEM) is used to compute the rigid Green's functions (with the code COFFEE). The method is first tested on simple geometries for which analytic solutions can be determined (sphere, cylinder, half plane). Then in order to consider realistic geometries in a reasonable amount of time, fast BEMs are used: fast multipole accelerated BEM and hierarchical matrix based BEM. The efficiencies of these two approaches are compared on realistic geometries of interest for the industrial partner (NACA profiles, boat propeller). Importantly, this first comparative study in an industrial context highlights the robustness of hierarchical matrix based BEM even though there are shown theoretically to be less optimal than fast multipole accelerated BEM. A publication is ongoing.

Improvements of hierarchical matrix based Boundary Element Methods for visco-elastodynamic problems

Participants Laura Bagur, Stéphanie Chaillat, Patrick Ciarlet, Sara Touhami.

It is well known in the literature that standard $\mathcal{H}$-matrix based methods, although very efficient tools for asymptotically smooth kernels, are not optimal for oscillatory kernels. In a previous work, we have shown that the method is already an efficient tool and should be used in the mechanical engineering community due to its straightforward implementation compared to $\mathcal{H}^2$-matrix, or directional, approaches.

We are currently investigating two possible improvements of this approach. Since in practice, not all materials are purely elastic it is important to be able to consider visco-elastic cases. In this context, we study the effect of the introduction of a complex wavenumber on the accuracy and efficiency of hierarchical matrix ($\mathcal{H}$-matrix) based fast methods for solving dense linear systems arising from the discretization of the elastodynamic Green's tensors. Interestingly, such configurations are also encountered in the context of the solution of transient purely elastic problems with the convolution quadrature method. Then, since $\mathcal{H}$-matrices are an automatic tool to remove redundant informations, we are studying its efficiency in the context of realistic sedimentary basins with high velocity contrasts. Fast multipole accelerated Boundary Element Methods have been shown to be inefficient in this context due to the need to use an over refined mesh for one of the two connected domains.

Asymptotic based methods for very high frequency problems.

Participants Eric Lunéville.

This research is developed in collaboration with Marc Lenoir and Daniel Bouche (CEA).

It has recently been realized that the combination of integral and asymptotic methods was a remarkable and necessary tool to solve scattering problems, in the case where the frequency is high and the geometry must be finely taken into account.

In order to implement the high-frequency approximations that we are developing as part of these hybrid HF/BF methods, we have introduced new geometric tools into the XLiFE++ library, in particular splines and B-Splines approximations as well as parameterizations to access quantities such as curvature, curvilinear abscissa, etc. We have also started to interface the OpenCascad library to the XLiFE++ library, which will eventually allow us to manage more complex geometric situations (cylinder and sphere intersection for example). In parallel, we have completed the implementation of 2D HF approximations in the shadow-light transition zone based on the Fock function. Diffraction by a 2D corner is in progress.

Solving elastodynamics equations with potentials and finite elements.

Participants Joly Patrick.

Work done in collaboration with Sebastien Imperiale (Inria EPI M3DISIM) and Alexandre Imperiale (CEA-LIST).

This work is the major theme of our collaboration with the University of Saint-Jacques de Compostelle (Jeronimo Rodríguez, Jorge Albella – whose PhD thesis was defended in March 2019). When solving 2D linear elastodynamic equations in a homogeneous isotropic media, a Helmholtz decomposition of the displacement field decouples the equations into two scalar wave equations that only interact at the boundary. It is then natural to look for numerical schemes that independently solve the scalar equations and couple the solutions at the boundary. This is expected to be very efficient to handle soft tissues for instance.

The case of rigid boundary condition was treated first and, in a second step, the case of free surface boundary condition was proven to be unstable if a straightforward approach is used. Then an original and adequate functional framework as well as a time domain mixed formulation to circumvent these issues were proposed.

Subsequently, we proposed a discrete formulation based on finite elements. We provided the complete stability analysis of the corresponding numerical scheme. The work has been accepted in Mathematics of Computation, in which numerical results that illustrate the theory are also shown.

The most recent developments concern the transmission problems between homogeneous media, which was our initial and ultimate goal, and for which the above mentioned approach has been successfully adapted to the treatment of interface conditions. The elaboration of this work and the design and implementation of efficient algorithms will be the subject of forthcoming developments.

Implicit-explicit scheme for elastodynamic equations in plates

Participants Sonia Fliss, Hajer Methenni.

Work done in collaboration with Sebastien Imperiale (Inria EPI M3DISIM) and Alexandre Imperiale (CEA-LIST). Our objective is to provide an efficient simulation tool for the propagation of elastic waves in thin plates in the context of Guided Waves based Structural Health Monitoring. A naive discretization procedure based on a Leap-frog explicit scheme can be really costly because of the small thickness of the plate. By treating implicitly the operators corresponding to derivatives through the thickness, we show by a stability analysis that the time step is less restricted by the space discretization along the thickness. The price to pay is to solve at each iteration small independent linear systems, but this strategy offers an accurate and efficient discretization of the elastic fields in all dimensions. This method can be used to compute reference solutions and verify the validity of asymptotic models such as Reissner–Mindlin model and some extensions (since there exists no rigorous justifications for elastodynamic problems). Finally under some conditions on the mesh, our approach can be extended to plates with a smoothly varying thickness.

7.2.3 Inverse problems for imaging and shape optimization

Imaging junctions of waveguides

Participants Laurent Bourgeois, Fliss Sonia, Fritsch Jean-François, Hazard Christophe.

A new activity has just started concerning forward and inverse scattering in junctions of waveguides. It corresponds to the PHD of Jean-François Fritsch and is a collaboration with the CEA-List, in particular Arnaud Recoquillay. Firstly, we have considered the junction between several closed waveguides. It is well-known that defects such as cracks often occur in weld bead of metallic pipes, which can be seen as junctions of waveguides. This explains why it is necessary to adapt Non Destructive Testing procedures to that kind of configuration. Forward scattering problems in junctions of closed waveguides are quite standard and can be solved with classical finite element methods coupled with transparent boundary conditions using Dirichlet to Neumann maps. However, solving inverse scattering problems for such geometries is less standard. In order to cope with those problems, we use a modal version of the classical Colton-Kirsch Linear Sampling Method. The main issue stems from the fact the LSM relies on the fundamental solution, which does not have a closed-form expression in a junction of waveguides, contrary to the case of a homogeneous waveguide. In order to cope with this problem, the main ingredient we introduce is the so-called reference fields, which are the responses of the junction without any defect to the guided modes considered as incident waves. We also use the symmetry property of the fundamental solution. The reference fields enable us to adapt the LSM by paying a reasonable computational cost, in the sense that it is not necessary to actually compute the fundamental solution for each sampling point of the grid. We have shown the feasibility of our method with the help of two-dimensional acoustic numerical experiments, for instance in the case of a junction of three waveguides.

Secondly, we have considered the more challenging case of a closed waveguide which is embedded in an open waveguide. A typical situation is the case of a cable which is partially embedded into another elastic medium, the cable being for example made of steel while the surrounding medium is made of concrete. It may happen that some defects within the embedded part of the cable or at the interface between the cable and the surrounding medium have to be retrieved from measurements located on the only accessible part of the cable, that is its free part. In a first attempt we have simplified the problem by considering a two-dimensional acoustic problem. Despite such simplification, both the forward and the inverse scattering problems are challenging. We address the forward problem by using Perfectly Matched Layers in the transverse direction, which has the effect of closing the waveguide but of introducing a non-selfadjoint eigenvalue problem in the transverse direction. At the continuous level, we use the Kondratiev approach to establish well-posedness of the forward problem and to specify the asymptotic behaviour of solutions at infinity. In a view to compute a numerical solution, we also introduce transparent boundary conditions in the infinite direction of the waveguide, involving either a Dirichlet to Neumann map or a Poynting to Neumann map. This latter amounts to a transparent thick boundary condition. We currently try to prove that these transparent boundary conditions are consistent. We have addressed the inverse problem with the help of the modal Linear Sampling Method by using the same ingredient as introduced in the previous case of the junction of closed waveguides. However a new difficulty arises since an open waveguide is characterized by radiation losses, which can be seen as lost information from the point of view of the inverse problem. In the case of a steel cable embedded into a concrete medium, this is all the more difficult as the speed in the core is larger than the speed in the sheath. As a consequence, once we have replaced the infinite medium by PMLs, the guided modes are either leaky modes or PML modes, both of them being evanescent. In this sense, the inverse problem is more challenging than in the case of closed waveguides, which benefit from a finite number of propagating modes. However, the numerical experiments that we have made seem to show that the LSM is efficient to retrieve defects provided they are sufficiently close to the interface between the closed and the open waveguide.

Modified forward and inverse Born series for the Calderon and diffuse-wave problems

Participants Marc Bonnet.

Work done in collaboration with Anuj Abischek and Shari Moskow, Drexel University, USA.

This investigation proposes a new direct reconstruction method based on series inversion for Electrical Impedance Tomography (EIT) and the inverse scattering problem for diffuse waves. The standard Born series for the forward problem has the limitation that the contrast lies within a certain radius for convergence. Here, we instead propose a modified Born series, based on our previous work on alternative formulations of volume integral equations, which converges for the forward problem unconditionally on the contrast. We then invert this modified Born series and compare reconstructions with the usual inverse Born series, showing that the proposed modified inverse Born series has a larger radius of convergence.

Asymptotic model for elastodynamic scattering by a small surface-breaking defect

Participants Marc Bonnet.

Work done in collaboration with Marc Deschamps and Eric Ducasse, I2M, Bordeaux.

We establish a leading-order asymptotic model for the scattering of elastodynamic fields by small surface-breaking defects in elastic solids. The asymptotic form of the representation formula of the scattered field is written in terms of the elastodynamic Green's tensor, which is in fact available in semi-analytical form for some geometrical configurations that are of practical interest in ultrasonic NDT configurations. A rigorous proof of the resulting leading asymptotic approximation is obtained. Preliminary numerical examples have been performed on cylindrical elastic pipes with small indentations on the outer surface.

Shape optimization problems involving slow viscous fluids

Participants Marc Bonnet.

Work done in collaboration with Shravan Veerapaneni and his group, University of Michigan, USA.

This collaboration addresses various shape optimization problems involving slow viscous fluid flows modelled by the Stokes equations. We have developed a new boundary integral approach for finding optimal shapes of peristaltic pumps that transport a viscous fluid. Formulas for computing the shape derivatives of the standard cost functionals and constraints, expressed in boundary-only form, are derived. They involve evaluating physical variables (traction, pressure, etc.) on the boundary only. By employing these formulas in conjunction with a boundary integral approach for solving forward and adjoint problems, we completely avoid the issue of volume remeshing when updating the pump shape as the optimization proceeds. This leads to significant cost savings and we demonstrate the performance on several numerical examples. We also investigate the optimization of the slip velocity (modeling cilia beating) and the shape of self-propelled micro-swimmers, so as to achieve self-propelling at least energy expense.

8 Bilateral contracts and grants with industry

8.1 Bilateral Contracts with Industry

- 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: ENSTA
- Contract with DGA and Naval Group on *transient fluid-structure coupling caused by remote underwater explosions, including cavitation effects*
  Participants: M. Bonnet, S. Chaillat, A. Nassor
  Start: 10/2020. End: 09/2023. Administrator: CNRS
- Contract and CIFRE PhD with CEA on *Modelling of thin layers of randomly distributed nanoparticles for electromagnetic waves*
  Participants: A. Boucart, S. Fliss, L. Giovangigli
  Start: 10/2019. End: 09/2022. Administrator: ENSTA
- Contract and CIFRE PhD with Naval Group on *flow noise prediction*
  Participants: J-F Mercier, B. Cotté, N. Trafny
  Start: 04/2018. End: 03/2021. Administrator: ENSTA

9 Partnerships and cooperations

9.1 National Initiatives

ANR

- ANR project NonlocalDD *(Non-local domain decomposition methods in electromagnetics)*
  Partners: Inria Alpines, Inria POEMS, Inria Magique 3D

Start: 10/2015. End: 09/2020. 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)

- ANR JCJC project FAsTD *(Flame Acceleration and Transition to Detonation in Narrow Channels)*
  Partners: INRIA (POEMS), CNRS (Institut Pprime)
  Start: 12/2020. End: 12/2024. Administrator: CNRS
  Participant of POEMS: L. Faria
  Coordinator: J. Melguizo Gavilanes (Institut Pprime)

DGA

- Contracts between DGA and POEMS:
  - Contract on *boundary element methods and high-frequency problems*
    Participants: E. Lunéville, M. Lenoir, N. Kielbasiewicz.
    Start: 10/2018. End: 09/2021. Administrator: ENSTA
    In partnership with F. Alouges and M. Aussal (CMAP, Ecole Polytechnique).

- DGA provides partial funding for several PhD students:
  - C. Bénéteau 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)
  - A. Nassor on *transient fluid-structure coupling caused by remote underwater explosions, including cavitation effects* (Start: 10/2020)

10 Dissemination

10.1 Promoting Scientific Activities

10.1.1 Scientific Events: Organisation

Member of the Organizing Committees

- Most of the permanent members of POEMS are involved in the organization of the 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation (organizing committee chaired by Sonia Fliss and Christophe Hazard). The conference was initially scheduled for July 26-30, 2021. This particular edition will be an opportunity to celebrate a double anniversary: the 15th occurrence of the conference, which coincides with its 30 years birthday! Unfortunately, due to the Covid situation, we have decided to postpone it to July 25-29, 2022. The conference will be held at ENSTA-Paris. Our wish is that this scientific meeting will also be a human meeting, taking advantage of the structure of ENSTA-Paris to receive on site in "full board" all participants who wish it. Website: www.waves2022.fr.

- S. Chaillat is a co-animator of the topic *"Modeling and simulation"* of the GDR Ondes (`https://gdr-ondes.cnrs.fr/`). Within this framework, she co-organizes a webinar series.

- J.-F. Mercier is a co-animator of the topic *"Effective dynamics of microstructured media"* of the GDR MecaWave (`https://mecawave.cnrs.fr/`).

- A. Modave co-organized with M. Bonazzoli (INRIA/Defi), T. Chaumont-Frelet (INRIA/Atlantis) and B. Thierry (CNRS/UPMC) a Young Researchers' Meeting on "Numerical simulation of waves in the time-harmonic regime", held virtually on November 23-24, 2020 (10 talks, about 40 registrated participants). Event website: https://jcjc_ondes.pages.math.cnrs.fr/

10.1.2 Journals

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*, *Computational Mechanics* and *Inverse Problems in Science and Engineering*.
- 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.

Reviewer - Reviewing Activities The team members regularly review papers for many international journals.

10.1.3 Research Administration

- A. S. Bonnet-Ben Dhia is deputy-chair of the *Applied Mathematics Department* (UMA) at ENSTA Paris.
- M. Bonnet is a member of the COMEVAL, a committee of the Ministry of Ecological and Inclusive Transition (MEIT) similar to a CNRS National Committee section and tasked with the recruiting and career overseeing of the cadre of junior and senior scientists managed by MEIT.
- S. Chaillat is a member of the CNRS National Committee for Scientific Research (Section 9: Solid mechanics, materials and structures, biomechanics, acoustics.)
- P. Ciarlet is coordinator of the *Mathematics in Computational Science and Engineering Program* of the Mathematics Hadamard Labex (LMH).
- E. Bécache is a deputy chair of the Doctoral School EDMH.

10.2 Teaching - Supervision - Juries

10.2.1 Administration

Permanent members of POEMS are involved in the management of the engineering program at ENSTA Paris, the program in applied mathematics at IP Paris, the master 2 program "Analyse, Modélisation et Simulation" (M1 AMS) and the master 2 program "Modélisation et Simulation en Mécanique des Structures et Systèmes Couplés" (M2 MS2SC) of Université Paris-Saclay:

- M. Bonnet: co-chair of the M2 MS2SC (ended with completion of 2019-20 academic year).
- L. Bourgeois: co-chair of second-year studies, ENSTA (since Sept. 2019); co-chair of the M1 in applied mathematics (since Sept. 2019).
- P. Ciarlet: coordinator of the master program in applied mathematics at IP Paris;
- S. Fliss: co-chair of the M2 AMS and co-chair of third-year studies, ENSTA.
- L. Giovangigli: in charge of the third year quantitative finance specialization at ENSTA.

10.2.2 Courses taught

The permanent members of POEMS teach in the engineering program at ENSTA Paris and the master program *"Analyse, Modélisation et Simulation"* (AMS) of Institut Polytechnique de Paris, and participate in miscellaneous other teaching activities.

- Eliane Bécache
  - *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA (1st year)
  - *Analyse et approximation par éléments finis d'EDP*, ENSTA (2nd year) and Master AMS (M1)
  - *Equations intégrales et potentiels retardés*, ENSTA (3rd year) and Master AMS (M2)
- Marc Bonnet
  - *Problème inverses et Identification*, Master MS2SC (M2)
- Anne-Sophie Bonnet-Ben Dhia
  - *Fonctions de variable complexe*, ENSTA (1st year)
  - *Théorie spectrale des opérateurs autoadjoints*, ENSTA (2nd year) and Master AMS (M1)
  - *Méthodes variationnelles pour l'analyse et la résolution de problèmes non coercifs*, ENSTA (3rd year) and Master AMS (M2)
  - *Problèmes de diffraction en domaines non bornés*, ENSTA (3rd year) and Master AMS (M2)
- Laurent Bourgeois
  - *Outils élémentaires pour l'analyse des équations aux dérivées partielles*, ENSTA (1st year)
  - *Fonctions de variable complexe*, ENSTA (1st year)
  - *Problémes inverses pour des systémes gouvernés par des EDPs*, ENSTA (3rd year) and Master AMS (M2)
- Stéphanie Chaillat
  - *Introduction à la discrétisation des équations aux dérivées partielles*, ENSTA (1st year)
  - *Techniques numériques et algorithmiques pour les équations intégrales*, ENSTA (3rd year), ENSTA (3rd year) and Master AMS (M2)
- 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)
  - *Méthodes variationnelles pour l'analyse et la résolution de problèmes non coercifs*, ENSTA (3rd year) and Master AMS (M2)
  - *Modèles mathématiques et leur discrétisation en électromagnétisme*, ENSTA (3rd year) and Master AMS (M2)
- Luiz Faria
  - *Programmation scientifique en C++*, ENSTA (2nd year) and Master AMS (M1)
- 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), ENSTA (3rd year) and Master AMS (M2)
- Laure Giovangigli
  - *Introduction aux probabilités et aux statistiques*, ENSTA (1st year)
  - *Martingales et algorithmes stochastiques*, ENSTA (2nd year)
  - *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)
  - *Analyse fonctionnelle*, ENSTA (2nd year) and Master AMS (M2)
  - *Techniques de discrétisation avancées pour les problèmes d'évolution*, ENSTA (3rd year) and Master AMS (M2)
- Maryna Kachanovska
  - *Fonctions de variable complexe*, ENSTA (1st year)
  - *Analyse fonctionnelle*, ENSTA (2nd year) and Master AMS (M1)
  - *Modèles mathématiques et leur discrétisation en électromagnétisme*, ENSTA (3rd year) and Master AMS (M2)
  - *Equations intégrales et potentiels retardés*, ENSTA (3rd year) and Master AMS (M2)
- 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)
  - *Problèmes de diffraction en domaines non bornés*, 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
  - *Calcul scientifique à haute performance*, ENSTA (2rd year) and Master AMS (M1)
  - *Calcul scientifique parallèle*, ENSTA (3rd year) and Master AMS (M2)

10.2.3 Supervision

- PhD: Sandrine Paolantoni, *"Analyse spectrale et simulation numérique de la diffraction électromagnétique par des métamatériaux"*, October 2020, C. Hazard
- PhD: Emile Parolin, *"Non overlapping domain decomposition methods with non local transmission conditions for electromagnetic wave propagation"*, October 2020, P. Joly and X. Claeys
- PhD: Damien Mavaleix-Marchessoux, *"Modeling of the fluid-structure interaction resulting from a remote underwater explosion"*, December 2020, M. Bonnet and S. Chaillat
- PhD in progress: Clément Bénéteau, *"Asymptotic analysis of time harmonic Maxwell equations in presence of metamaterials"*, October 2017, S. Fliss and X. Claeys
- PhD in progress: Hajer Methenni, *"Mathematical modelling and numerical method for the simulation of ultrasound structural health monitoring of composite plates"*, October 2017, S. Fliss and S. Impériale
- PhD in progress: Nicolas Trafny, *"Development of semi-analytical models to predict the noise produced by turbulence-edges interactions"*, April 2018, J.-F. Mercier and B. Cotté
- PhD in progress: Damien Chicaud, *"Méthodes de décomposition de domaine pour la résolution de problèmes harmoniques d'ondes électromagnétiques en milieux complexes"*, October 2018, P. Ciarlet and A. Modave
- PhD in progress: Mahran Rihani, *"Équations de Maxwell en présence de méta-matériaux"*, November 2018, A.-S. Bonnet-Ben Dhia and L. Chesnel
- PhD in progress: Akram Beni Hamad, *"Propagation d'ondes électromagnétiques dans les cables coaxiaux"*, Septembre 2019, S. Imperiale, P. Joly and M. Khenissi
- PhD in progress: Jean-François Fritsch, *"Imagerie dans les guides d'ondes enfouis"*, Octobre 2019, L. Bourgeois and C. Hazard
- PhD in progress: Amandine Boucart *"Modélisation d'une couche mince de nanoparticules réparties aléatoirement pour les ondes électromagnétiques*, Octobre 2019, S. Fliss and L. Giovangigli
- PhD in progress: Amond Allouko, *"Approche semi-analytique hybride utilisant les guides d'ondes et la méthode des éléments finis pour le contrôle de santé intégrée de plaques composites"*, September 2020, A.-S. Bonnet and A. Lhemery
- PhD in progress: Laura Bagur, *"Three dimensional modeling of seismic and aseismic slip using Fast Boundary Element Methods"*, September 2020, S. Chaillat, J.-F. Samblat and I. Stéfanou
- PhD in progress: Pierre Amenoagbadji, *"Propagation des ondes dans des milieux quasi-périodiques"*, Octobre 2020, S. Fliss and P. Joly
- PhD in progress: Etienne Peillon, *"Justification et analyse mathématique de modèles de métamatériaux hyperboliques"*, Octobre 2020, P. Ciarlet and M. Kachanovska
- PhD in progress: Alice Nassor, *"Transient fluid-structure coupling caused by remote underwater explosions, including cavitation effects"*, Octobre 2020, S. Chaillat and M. Bonnet
- PhD in progress: Alejandro Rosas Martinez Luis, *"Dispersive electromagnetic media: mathematical and numerical analysis"*, November 2020, M. Cassier and P. Joly

11 Scientific production

11.1 Publications of the year

International journals

[1] A. Abhishek, M. Bonnet and S. Moskow. 'Modified forward and inverse Born series for the Calderon and diffuse-wave problems'. In: *Inverse Problems* 36 (2020), p. 114001. DOI: 10.1088/1361-6420/abae11. URL: https://hal.archives-ouvertes.fr/hal-02571381.

[2] J. Albella Martínez, S. Imperiale, P. Joly and J. Rodríguez. 'Numerical Analysis of a Method for Solving 2D Linear Isotropic Elastodynamics with Free Boundary Condition using Potentials and Finite Elements'. In: *Mathematics of Computation* (2021). DOI: 10.1007/s10915-018-0768-9. URL: https://hal.inria.fr/hal-02345808.

[3] E. Bécache, S. Fliss, M. Kachanovska and M. Kazakova. 'On a surprising instability result of Perfectly Matched Layers for Maxwell's equations in 3D media with diagonal anisotropy'. In: *Comptes Rendus Mathématique* (2021). URL: https://hal.archives-ouvertes.fr/hal-02873620.

[4] G. Beck, S. Imperiale and P. Joly. 'Asymptotic modelling of Skin-effects in coaxial cables'. In: *SN Partial Differential Equations and Applications* (Oct. 2020). URL: https://hal.inria.fr/hal-02512156.

[5] A. Bera, A.-S. Bonnet-Ben Dhia and L. Chesnel. 'A continuation method for building invisible obstacles in waveguides'. In: *Quarterly Journal of Mechanics and Applied Mathematics* (26th Feb. 2021). URL: https://hal.archives-ouvertes.fr/hal-02573706.

[6] H. Beriot and A. Modave. 'An automatic PML for acoustic finite element simulations in convex domains of general shape'. In: *International Journal for Numerical Methods in Engineering* 122.5 (2021), pp. 1239–1261. DOI: 10.1002/nme.6560. URL: https://hal.archives-ouvertes.fr/hal-02738261.

[7] M. Bonnet, R. Liu and S. Veerapaneni. 'Shape optimization of Stokesian peristaltic pumps using boundary integral methods'. In: *Journal of Computational and Applied Mathematics* 46 (2020), p. 18. DOI: 10.1007/s10444-020-09761-7. URL: https://hal.archives-ouvertes.fr/hal-02064507.

[8] L. Bourgeois and L. Chesnel. 'On quasi-reversibility solutions to the Cauchy problem for the Laplace equation: regularity and error estimates'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* (Mar. 2020). DOI: 10.1051/m2an/2019073. URL: https://hal.inria.fr/hal-02385487.

[9] L. Bourgeois, J.-F. Fritsch and A. Recoquillay. 'Imaging junctions of waveguides'. In: *Inverse Problems and Imaging* (Feb. 2021). DOI: 10.3934/ipi.2020065. URL: https://hal.inria.fr/hal-02567182.

[10] L. Bourgeois and C. Hazard. 'On well-posedness of scattering problems in a Kirchhoff-Love infinite plate'. In: *SIAM Journal on Applied Mathematics* 80.3 (2020), pp. 1546–1566. URL: https://hal-ensta-paris.archives-ouvertes.fr//hal-02334004.

[11] L. Bourgeois and A. Recoquillay. 'The Linear Sampling Method for Kirchhoff-Love Infinite Plates'. In: *Inverse Problems and Imaging* (Apr. 2020). DOI: 10.3934/ipi.2020065. URL: https://hal.inria.fr/hal-02269910.

[12] R. Bunoiu, L. Chesnel, K. Ramdani and M. Rihani. 'Homogenization of Maxwell's equations and related scalar problems with sign-changing coefficients'. In: *Annales de la Faculté des Sciences de Toulouse. Mathématiques.* (2020). URL: https://hal.inria.fr/hal-02421312.

[13] D. Chicaud, P. Ciarlet and A. Modave. 'Analysis of variational formulations and low-regularity solutions for time-harmonic electromagnetic problems in complex anisotropic media'. In: *SIAM Journal on Mathematical Analysis* (2021). URL: https://hal.archives-ouvertes.fr/hal-02651682.

[14] F. Ciardo, B. Lecampion, F. Fayard and S. Chaillat. ‘A fast boundary element based solver for localized inelastic deformations’. In: *International Journal for Numerical Methods in Engineering* 121.24 (Dec. 2020), pp. 5696–5718. DOI: 10.1002/nme.6520. URL: https://hal.archives-ouvertes.fr/hal-02997409.

[15] P. Ciarlet. ‘On the approximation of electromagnetic fields by edge finite elements. Part 3: sensitivity to coefficients’. In: *SIAM Journal on Mathematical Analysis* (2020). URL: https://hal.inria.fr/hal-02276430.

[16] F. Collino, P. Joly and M. Lecouvez. ‘Exponentially convergent non overlapping domain decomposition methods for the Helmholtz equation’. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 54.3 (May 2020), pp. 775–810. DOI: 10.1051/m2an/2019050. URL: https://hal-cea.archives-ouvertes.fr/cea-03052206.

[17] S. Fliss and L. Giovangigli. ‘Time harmonic wave propagation in one dimensional weakly randomly perturbed periodic media’. In: *SN Partial Differential Equations and Applications* 1.40 (Oct. 2020). URL: https://hal.inria.fr/hal-02504392.

[18] H. Guo, H. Zhu, R. Liu, M. Bonnet and S. Veerapaneni. ‘Optimal slip velocities of micro-swimmers with arbitrary axisymmetric shapes’. In: *Journal of Fluid Mechanics* 910 (2021), A26. DOI: 10.1017/jfm.2020.969. URL: https://hal.archives-ouvertes.fr/hal-03099172.

[19] C. Hazard and S. Paolantoni. ‘Spectral analysis of polygonal cavities containing a negative-index material’. In: *Annales Henri Lebesgue* 3 (2020), pp. 1161–1193. DOI: 10.5802/ahl.58. URL: https://hal-ensta-paris.archives-ouvertes.fr//hal-01626868.

[20] P. Joly and M. Kachanovska. ‘Transparent boundary conditions for wave propagation in fractal trees: convolution quadrature approach’. In: *Numerische Mathematik* 146(2) (Sept. 2020), pp. 281–334. URL: https://hal.archives-ouvertes.fr/hal-02265345.

[21] F. D. Kpadonou, S. Chaillat and P. Ciarlet. ‘On the efficiency of nested GMRES preconditioners for 3D acoustic and elastodynamic H-matrix accelerated Boundary Element Methods’. In: *Computers and Mathematics with Applications* 80.3 (1st Aug. 2020). DOI: 10.1016/j.camwa.2020.03.021. URL: https://hal.archives-ouvertes.fr/hal-02415902.

[22] L. Maltez Faria, C. Pérez-Arancibia and M. Bonnet. ‘General-purpose kernel regularization of \linebreak boundary integral equations via density interpolation’. In: *Computer Methods in Applied Mechanics and Engineering* 378 (2021), p. 113703. DOI: 10.1016/j.cma.2021.113703. URL: https://hal.archives-ouvertes.fr/hal-02964015.

[23] D. Mavaleix-Marchessoux, M. Bonnet, S. Chaillat and B. Leblé. ‘A fast BEM procedure using the Z-transform and high-frequency approximations for large-scale 3D transient wave problems’. In: *International Journal for Numerical Methods in Engineering* 121 (2020), pp. 4734–4767. URL: https://hal.archives-ouvertes.fr/hal-02515371.

[24] J. Melguizo-Gavilanes, Y. Ballossier and L. Maltez Faria. ‘Experimental and theoretical observations on DDT in smooth narrow channels’. In: *Proceedings of the Combustion Institute* (Oct. 2020). DOI: 10.1016/j.proci.2020.07.142. URL: https://hal.archives-ouvertes.fr/hal-02989874.

[25] A. Modave, C. Geuzaine and X. Antoine. ‘Corner treatments for high-order local absorbing boundary conditions in high-frequency acoustic scattering’. In: *Journal of Computational Physics* 401 (2020), p. 109029. DOI: 10.1016/j.jcp.2019.109029. URL: https://hal.archives-ouvertes.fr/hal-01925160.

[26] A. Modave, A. Royer, X. Antoine and C. Geuzaine. ‘A non-overlapping domain decomposition method with high-order transmission conditions and cross-point treatment for Helmholtz problems’. In: *Computer Methods in Applied Mechanics and Engineering* 368 (15th Aug. 2020), \linebreak 1131622020. DOI: 10.1016/j.cma.2020.113162. URL: https://hal.archives-ouvertes.fr/hal-02432422.

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[28] C. Pérez-Arancibia, C. Turc, L. Faria and C. Sideris. 'Planewave Density Interpolation Methods for the EFIE on Simple and Composite Surfaces'. In: *IEEE Transactions on Antennas and Propagation* (16th July 2020). URL: https://hal.archives-ouvertes.fr/hal-02429487.

[29] K. Pham, A. Maurel, J.-F. Mercier, S. Félix, M. L. Cordero and C. Horvath. 'Perfect Brewster transmission through ultrathin perforated films'. In: *Wave Motion* 93 (1st Mar. 2020), p. 102485. DOI: 10.1016/j.wavemoti.2019.102485. URL: https://hal.archives-ouvertes.fr/hal-03089421.

[30] K. Pham, J.-F. Mercier, D. Fuster, J.-J. Marigo and A. Maurel. 'Scattering of acoustic waves by a nonlinear resonant bubbly screen'. In: *Journal of Fluid Mechanics* 906 (2021), A19. DOI: 10.1017/jfm.2020.799. URL: https://hal.archives-ouvertes.fr/hal-03024405.

Scientific book chapters

[31] X. Claeys, F. Collino, P. Joly and E. Parolin. 'A Discrete Domain Decomposition Method for Acoustics with Uniform Exponential Rate of Convergence Using Non-local Impedance Operators'. In: *Domain Decomposition Methods in Science and Engineering XXV*. 25th Oct. 2020, pp. 310–317. DOI: 10.1007/978-3-030-56750-7_35. URL: https://hal.archives-ouvertes.fr/hal-03118734.

Doctoral dissertations and habilitation theses

[32] C. Beneteau. 'Enriched homogenized models in presence of boundaries : analysis and numerical treatment'. Institut Polytechnique de Paris, 20th Jan. 2021. URL: https://tel.archives-ouvertes.fr/tel-03160431.

[33] S. Bernard Paolantoni. 'Spectral analysis and numerical simulation of cavities containing a negative material'. Institut Polytechnique de Paris, 15th Oct. 2020. URL: https://tel.archives-ouvertes.fr/tel-02996725.

[34] D. Mavaleix-Marchessoux. 'Modelling the fluid-structure coupling caused by a far-field underwater explosion'. Institut Polytechnique de Paris, 10th Dec. 2020. URL: https://tel.archives-ouvertes.fr/tel-03145479.

[35] É. Parolin. 'Non-overlapping domain decomposition methods with non-local transmissionoperators for harmonic wave propagation problems'. Institut Polytechnique de Paris, 4th Dec. 2020. URL: https://tel.archives-ouvertes.fr/tel-03118712.

Reports & preprints

[36] E. Bécache and M. Kachanovska. *Stability and Convergence Analysis of Time-domain Perfectly Matched Layers for The Wave Equation in Waveguides*. 8th Apr. 2020. URL: https://hal.archives-ouvertes.fr/hal-02536375.

[37] A.-S. Bonnet-Ben Dhia, M.-O. Bristeau, E. Godlewski, S. Imperiale, A. Mangeney and J. Sainte-Marie. *Pseudo-compressibility, dispersive model and acoustic waves in shallow water flows*. 29th May 2020. URL: https://hal.inria.fr/hal-02493518.

[38] A.-S. Bonnet-Ben Dhia, S. N. Chandler-Wilde, S. Fliss, C. Hazard, K.-M. Perfekt and Y. Tjandrawidjaja. *The Complex-Scaled Half-Space Matching Method*. 23rd Dec. 2020. URL: https://hal.inria.fr/hal-03087232.

[39] A.-S. Bonnet-Ben Dhia, L. Chesnel and M. Rihani. *Maxwell's equations with hypersingularities at a conical plasmonic tip*. 16th Oct. 2020. URL: https://hal.archives-ouvertes.fr/hal-02969739.

[40] A.-S. Bonnet-Ben Dhia, C. Hazard and F. Monteghetti. *Complex-scaling method for the plasmonic resonances of planar subwavelength particles with corners*. 26th Aug. 2020. URL: https://hal.archives-ouvertes.fr/hal-02923259.

[41] C. Carvalho, P. Ciarlet and C. Scheid. *Limiting amplitude principle and resonances in plasmonic structures with corners: numerical investigation*. 5th Mar. 2021. URL: https://hal.archives-ouvertes.fr/hal-03160574.

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