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Activity Report 2017

Project-Team DEFI

Shape reconstruction and identification

IN COLLABORATION WITH: Centre de Mathématiques Appliquées (CMAP)

RESEARCH CENTER
Saclay - Île-de-France

THEME
Numerical schemes and simulations

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Project-Team DEFI

Creation of the Project-Team: 2009 January 01

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A6.2. - Scientific Computing, Numerical Analysis & Optimization
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Other Research Topics and Application Domains:

B1.2.1. - Understanding and simulation of the brain and the nervous system
B2.6.1. - Brain imaging
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1. Personnel

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2. Overall Objectives

2.1. Overall Objectives

The research activity of our team is dedicated to the design, analysis and implementation of efficient numerical methods to solve inverse and shape/topological optimization problems in connection with acoustics, electromagnetism, elastodynamics, and diffusion.

Sought practical applications include radar and sonar applications, bio-medical imaging techniques, non-destructive testing, structural design, composite materials, and diffusion magnetic resonance imaging.

Roughly speaking, the model problem consists in determining information on, or optimizing the geometry (topology) and the physical properties of unknown targets from given constraints or measurements, for instance, measurements of diffracted waves or induced magnetic fields.

In general this kind of problems is non-linear. The inverse ones are also severely ill-posed and therefore require special attention from regularization point of view, and non-trivial adaptations of classical optimization methods.

Our scientific research interests are the following:

- Theoretical understanding and analysis of the forward and inverse mathematical models, including in particular the development of simplified models for adequate asymptotic configurations.
- The design of efficient numerical optimization/inversion methods which are quick and robust with respect to noise. Special attention will be paid to algorithms capable of treating large scale problems (e.g. 3-D problems) and/or suited for real-time imaging.
- Development of prototype softwares for specific applications or tutorial toolboxes.

We were particularly interested in the development of the following themes

- Qualitative methods for inverse scattering problems
- Iterative and Hybrid inversion methods
- Topological optimization methods
- Forward and inverse models for Diffusion MRI
- Asymptotic models and methods for waves and diffusion.

3. Research Program

3.1. Research Program

The research activity of our team is dedicated to the design, analysis and implementation of efficient numerical methods to solve inverse and shape/topological optimization problems in connection with wave imaging, structural design, non-destructive testing and medical imaging modalities. We are particularly interested in the development of fast methods that are suited for real-time applications and/or large scale problems. These goals require to work on both the physical and the mathematical models involved and indeed a solid expertise in related numerical algorithms.

This section intends to give a general overview of our research interests and themes. We choose to present them through the specific academic example of inverse scattering problems (from inhomogeneities), which is representative of foreseen developments on both inversion and (topological) optimization methods. The practical problem would be to identify an inclusion from measurements of diffracted waves that result from the interaction of the sought inclusion with some (incident) waves sent into the probed medium. Typical applications include biomedical imaging where using micro-waves one would like to probe the presence of pathological cells, or imaging of urban infrastructures where using ground penetrating radars (GPR) one is interested in finding the location of buried facilities such as pipelines or waste deposits. This kind of applications requires in particular fast and reliable algorithms.

By “imaging” we refer to the inverse problem where the concern is only the location and the shape of the inclusion, while “identification” may also indicate getting informations on the inclusion physical parameters.

Both problems (imaging and identification) are non linear and ill-posed (lack of stability with respect to measurements errors if some careful constrains are not added). Moreover, the unique determination of the geometry or the coefficients is not guaranteed in general if sufficient measurements are not available. As an example, in the case of anisotropic inclusions, one can show that an appropriate set of data uniquely determine the geometry but not the material properties.

These theoretical considerations (uniqueness, stability) are not only important in understanding the mathematical properties of the inverse problem, but also guide the choice of appropriate numerical strategies (which information can be stably reconstructed) and also the design of appropriate regularization techniques. Moreover, uniqueness proofs are in general constructive proofs, i.e. they implicitly contain a numerical algorithm to solve the inverse problem, hence their importance for practical applications. The sampling methods introduced below are one example of such algorithms.

A large part of our research activity is dedicated to numerical methods applied to the first type of inverse problems, where only the geometrical information is sought. In its general setting the inverse problem is very challenging and no method can provide universally satisfying solution (respecting the balance cost-precision-stability). This is why in the majority of the practically employed algorithms, some simplification of the underlying mathematical model is used, according to the specific configuration of the imaging experiment. The most popular ones are geometric optics (the Kirchhoff approximation) for high frequencies and weak scattering (the Born approximation) for small contrasts or small obstacles. They actually give full satisfaction for a wide range of applications as attested by the large success of existing imaging devices (radar, sonar, ultrasound, X-ray tomography, etc.), that rely on one of these approximations.

In most cases, the used simplification result in a linearization of the inverse problem and therefore is usually valid only if the latter is weakly non-linear. The development of simplified models and the improvement of their efficiency is still a very active research area. With that perspective, we are particularly interested in deriving and studying higher order asymptotic models associated with small geometrical parameters such as: small obstacles, thin coatings, wires, periodic media, ... Higher order models usually introduce some non linearity in the inverse problem, but are in principle easier to handle from the numerical point of view than in the case of the exact model.

A larger part of our research activity is dedicated to algorithms that avoid the use of such approximations and that are efficient where classical approaches fail: i.e. roughly speaking when the non linearity of the inverse problem is sufficiently strong. This type of configuration is motivated by the applications mentioned below, and occurs as soon as the geometry of the unknown media generates non negligible multiple scattering effects (multiply-connected and closely spaces obstacles) or when the used frequency is in the so-called resonant region (wave-length comparable to the size of the sought medium). It is therefore much more difficult to deal with and requires new approaches. Our ideas to tackle this problem is mainly motivated and inspired by recent advances in shape and topological optimization methods and in so-called sampling methods.

Sampling methods are fast imaging solvers adapted to multi-static data (multiple receiver-transmitter pairs) at a fixed frequency. Even if they do not use any linearization the forward model, they rely on computing the solutions to a set of linear problems of small size, that can be performed in a completely parallel procedure.

Our team has already a solid expertise in these methods applied to electromagnetic 3-D problems. The success of such approaches was their ability to provide a relatively quick algorithm for solving 3-D problems without any need for a priori knowledge on the physical parameters of the targets. These algorithms solve only the imaging problem, in the sense that only the geometrical information is provided.

Despite the large efforts already spent in the development of this type of methods, either from the algorithmic point of view or the theoretical one, numerous questions are still open. These attractive new algorithms also suffer from the lack of experimental validations, due to their relatively recent introduction. We also would like to invest on this side by developing collaborations with engineering research groups that have experimental facilities. From the practical point of view, the most potential limitation of sampling methods would be the need of a large amount of data to achieve a reasonable accuracy. On the other hand, optimization methods do not suffer from this constrain but they require good initial guess to ensure convergence and reduce the number of iterations. Therefore it seems natural to try to combine the two class of methods in order to calibrate the balance between cost and precision.

Among various shape optimization methods, the Level Set method seems to be particularly suited for such a coupling. First, because it shares similar mechanism as sampling methods: the geometry is captured as a level set of an “indicator function” computed on a cartesian grid. Second, because the two methods do not require any a priori knowledge on the topology of the sought geometry. Beyond the choice of a particular method, the main question would be to define in which way the coupling can be achieved. Obvious strategies consist in using one method to pre-process (initialization) or post-process (find the level set) the other. But one can also think of more elaborate ones, where for instance a sampling method can be used to optimize the choice of the incident wave at each iteration step. The latter point is closely related to the design of so called “focusing incident waves” (which are for instance the basis of applications of the time-reversal principle). In the frequency regime, these incident waves can be constructed from the eigenvalue decomposition of the data operator used by sampling methods. The theoretical and numerical investigations of these aspects are still not completely understood for electromagnetic or elastodynamic problems.

Other topological optimization methods, like the homogenization method or the topological gradient method, can also be used, each one provides particular advantages in specific configurations. It is evident that the development of these methods is very suited to inverse problems and provide substantial advantage compared to classical shape optimization methods based on boundary variation. Their applications to inverse problems has not been fully investigated. The efficiency of these optimization methods can also be increased for adequate asymptotic configurations. For instance small amplitude homogenization method can be used as an efficient relaxation method for the inverse problem in the presence of small contrasts. On the other hand, the topological gradient method has shown to perform well in localizing small inclusions with only one iteration.

A broader perspective would be the extension of the above mentioned techniques to time-dependent cases. Taking into account data in time domain is important for many practical applications, such as imaging in cluttered media, the design of absorbing coatings or also crash worthiness in the case of structural design.

For the identification problem, one would like to also have information on the physical properties of the targets. Of course optimization methods is a tool of choice for these problems. However, in some applications only a qualitative information is needed and obtaining it in a cheaper way can be performed using asymptotic theories combined with sampling methods. We also refer here to the use of so called transmission eigenvalues as qualitative indicators for non destructive testing of dielectrics.

We are also interested in parameter identification problems arising in diffusion-type problems. Our research here is mostly motivated by applications to the imaging of biological tissues with the technique of Diffusion Magnetic Resonance Imaging (DMRI). Roughly speaking DMRI gives a measure of the average distance travelled by water molecules in a certain medium and can give useful information on cellular structure and structural change when the medium is biological tissue. In particular, we would like to infer from DMRI measurements changes in the cellular volume fraction occurring upon various physiological or pathological conditions as well as the average cell size in the case of tumor imaging. The main challenges here are 1) correctly model measured signals using diffusive-type time-dependent PDEs 2) numerically handle the complexity of the tissues 3) use the first two to identify physically relevant parameters from measurements.

For the last point we are particularly interested in constructing reduced models of the multiple-compartment Bloch-Torrey partial differential equation using homogenization methods.

4. Application Domains

4.1. Radar and GPR applications

Conventional radar imaging techniques (ISAR, GPR, etc.) use backscattering data to image targets. The commonly used inversion algorithms are mainly based on the use of weak scattering approximations such as the Born or Kirchhoff approximation leading to very simple linear models, but at the expense of ignoring multiple scattering and polarization effects. The success of such an approach is evident in the wide use of synthetic aperture radar techniques.

However, the use of backscattering data makes 3-D imaging a very challenging problem (it is not even well understood theoretically) and as pointed out by Brett Borden in the context of airborne radar: “In recent years it has become quite apparent that the problems associated with radar target identification efforts will not vanish with the development of more sensitive radar receivers or increased signal-to-noise levels. In addition it has (slowly) been realized that greater amounts of data - or even additional “kinds” of radar data, such as added polarization or greatly extended bandwidth - will all suffer from the same basic limitations affiliated with incorrect model assumptions. Moreover, in the face of these problems it is important to ask how (and if) the complications associated with radar based automatic target recognition can be surmounted.” This comment also applies to the more complex GPR problem.

Our research themes will incorporate the development, analysis and testing of several novel methods, such as sampling methods, level set methods or topological gradient methods, for ground penetrating radar application (imaging of urban infrastructures, landmines detection, underground waste deposits monitoring,) using multistatic data.

4.2. Biomedical imaging

Among emerging medical imaging techniques we are particularly interested in those using low to moderate frequency regimes. These include Microwave Tomography, Electrical Impedance Tomography and also the closely related Optical Tomography technique. They all have the advantage of being potentially safe and relatively cheap modalities and can also be used in complementarity with well established techniques such as X-ray computed tomography or Magnetic Resonance Imaging.

With these modalities tissues are differentiated and, consequentially can be imaged, based on differences in dielectric properties (some recent studies have proved that dielectric properties of biological tissues can be a strong indicator of the tissues functional and pathological conditions, for instance, tissue blood content, ischemia, infarction, hypoxia, malignancies, edema and others). The main challenge for these functionalities is to built a 3-D imaging algorithm capable of treating multi-static measurements to provide real-time images with highest (reasonably) expected resolutions and in a sufficiently robust way.

Another important biomedical application is brain imaging. We are for instance interested in the use of EEG and MEG techniques as complementary tools to MRI. They are applied for instance to localize epileptic centers or active zones (functional imaging). Here the problem is different and consists into performing passive imaging: the epileptic centers act as electrical sources and imaging is performed from measurements of induced currents. Incorporating the structure of the skull is primordial in improving the resolution of the imaging procedure. Doing this in a reasonably quick manner is still an active research area, and the use of asymptotic models would offer a promising solution to fix this issue.

4.3. Non destructive testing and parameter identification

One challenging problem in this vast area is the identification and imaging of defaults in anisotropic media. For instance this problem is of great importance in aeronautic constructions due to the growing use of composite materials. It also arises in applications linked with the evaluation of wood quality, like locating knots in timber in order to optimize timber-cutting in sawmills, or evaluating wood integrity before cutting trees. The anisotropy of the propagative media renders the analysis of diffracted waves more complex since one cannot only relies on the use of backscattered waves. Another difficulty comes from the fact that the micro-structure of the media is generally not well known a priori.

Our concern will be focused on the determination of qualitative information on the size of defaults and their physical properties rather than a complete imaging which for anisotropic media is in general impossible. For instance, in the case of homogeneous background, one can link the size of the inclusion and the index of refraction to the first eigenvalue of so-called interior transmission problem. These eigenvalues can be determined form the measured data and a rough localization of the default. Our goal is to extend this kind of idea to the cases where both the propagative media and the inclusion are anisotropic. The generalization to the case of cracks or screens has also to be investigated.

In the context of nuclear waste management many studies are conducted on the possibility of storing waste in a deep geological clay layer. To assess the reliability of such a storage without leakage it is necessary to have a precise knowledge of the porous media parameters (porosity, tortuosity, permeability, etc.). The large range of space and time scales involved in this process requires a high degree of precision as well as tight bounds on the uncertainties. Many physical experiments are conducted in situ which are designed for providing data for parameters identification. For example, the determination of the damaged zone (caused by excavation) around the repository area is of paramount importance since microcracks yield drastic changes in the permeability. Level set methods are a tool of choice for characterizing this damaged zone.

4.4. Diffusion MRI

In biological tissues, water is abundant and magnetic resonance imaging (MRI) exploits the magnetic property of the nucleus of the water proton. The imaging contrast (the variations in the grayscale in an image) in standard MRI can be from either proton density, T1 (spin-lattice) relaxation, or T2 (spin-spin) relaxation and the contrast in the image gives some information on the physiological properties of the biological tissue at different physical locations of the sample. The resolution of MRI is on the order of millimeters: the greyscale value shown in the imaging pixel represents the volume-averaged value taken over all the physical locations contained that pixel.

In diffusion MRI, the image contrast comes from a measure of the average distance the water molecules have moved (diffused) during a certain amount of time. The Pulsed Gradient Spin Echo (PGSE) sequence is a commonly used sequence of applied magnetic fields to encode the diffusion of water protons. The term 'pulsed' means that the magnetic fields are short in duration, an the term gradient means that the magnetic fields vary linearly in space along a particular direction. First, the water protons in tissue are labelled with nuclear spin at a precession frequency that varies as a function of the physical positions of the water molecules via the application of a pulsed (short in duration, lasting on the order of ten milliseconds) magnetic field. Because the precessing frequencies of the water molecules vary, the signal, which measures the aggregate phase of the water molecules, will be reduced due to phase cancellations. Some time (usually tens of milliseconds) after the first pulsed magnetic field, another pulsed magnetic field is applied to reverse the spins of the water molecules. The time between the applications of two pulsed magnetic fields is called the 'diffusion time'. If the water molecules have not moved during the diffusion time, the phase dispersion will be reversed, hence the signal loss will also be reversed, the signal is called refocused. However, if the molecules have moved during the diffusion time, the refocusing will be incomplete and the signal detected by the MRI scanner if weaker than if the water molecules have not moved. This lack of complete refocusing is called the signal attenuation and is the basis of the image contrast in DMRI. the pixels showning more signal attenuation is associated with further water displacement during the diffusion time, which may be linked to physiological factors, such as higher cell membrane permeability, larger cell sizes, higher extra-cellular volume fraction.

We model the nuclear magnetization of water protons in a sample due to diffusion-encoding magnetic fields by a multiple compartment Bloch-Torrey partial differential equation, which is a diffusive-type time-dependent PDE. The DMRI signal is the integral of the solution of the Bloch-Torrey PDE. In a homogeneous medium, the intrinsic diffusion coeffcient D will appear as the slope of the semi-log plot of the signal (in approporiate units). However, because during typical scanning times, 50-100ms, water molecules have had time to travel a diffusion distance which is long compared to the average size of the cells, the slope of the semi-log plot of the signal is in fact a measure of an 'effective' diffusion coefficient. In DMRI applications, this measured quantity is called the 'apparent diffusion coefficient' (ADC) and provides the most commonly used form the image contrast for DMRI. This ADC is closely related to the effective diffusion coefficient obtainable from mathematical homogenization theory.

5. New Software and Platforms

5.1. FVforBlochTorrey

- Participant: Jing Rebecca Li
- Contact: Jing Rebecca Li

5.2. InvGIBC

- Participant: Nicolas Chaulet
- Contact: Houssem Haddar

5.3. RODIN

FUNCTIONAL DESCRIPTION: In the framework of the RODIN project we continue to develop with our software partner ESI the codes Topolev and Geolev for topology and geometry shape optimization of mechanical structures using the level set method.

- Contact: Grégoire Allaire

5.4. samplings-2d

This software solves forward and inverse problems for the Helmholtz equation in 2-D.
FUNCTIONAL DESCRIPTION: This software is written in Fortran 90 and is related to forward and inverse problems for the Helmholtz equation in 2-D. It includes three independent components. * The first one solves to scattering problem using integral equation approach and supports piecewise-constant dielectrics and obstacles with impedance boundary conditions. * The second one contains various samplings methods to solve the inverse scattering problem (LSM, RGLSM(s), Factorization, MuSiC) for near-field or far-field setting. * The third component is a set of post processing functionalities to visualize the results

- Participant: Houssem Haddar
- Contact: Houssem Haddar
- URL: http://sourceforge.net/projects/samplings-2d/

5.5. Samplings-3d

FUNCTIONAL DESCRIPTION: This software is written in Fortran 90 and is related to forward and inverse problems for the Helmholtz equation in 3-D. It contains equivalent functionalities to samplings-2d in a 3-D setting.

- Contact: Houssem Haddar

5.6. SCILAB

SCIENTIFIC DESCRIPTION: Scilab includes hundreds of mathematical functions. It has a high level programming language allowing access to advanced data structures, 2-D and 3-D graphical functions.

A large number of functionalities is included in Scilab:

Maths & Simulation For usual engineering and science applications including mathematical operations and data analysis. 2-D & 3-D Visualization Graphics functions to visualize, annotate and export data and many ways to create and customize various types of plots and charts. Optimization Algorithms to solve constrained and unconstrained continuous and discrete optimization problems. Statistics Tools to perform data analysis and modeling Control System Design & Analysis Standard algorithms and tools for control system study Signal Processing Visualize, analyze and filter signals in time and frequency domains. Application Development Increase Scilab native functionalities and manage data exchanges with external tools. Xcos - Hybrid dynamic systems modeler and simulator Modeling mechanical systems, hydraulic circuits, control systems...
FUNCTIONAL DESCRIPTION: Scilab is free and open source software for numerical computation providing a powerful computing environment for engineering and scientific applications.

- Participant: Grégoire Allaire
- Contact: Grégoire Allaire
- URL: http://www.scilab.org/

6. New Results

6.1. Methods for inverse problems

6.1.1. The Generalized Linear Sampling Method for limited aperture measurements

L. Audibert and H. Haddar

We extend the so-called Generalized Linear Sampling Method (GLSM) to the case of limited aperture data at a fixed frequency. In this case the factorization of the sampling operator does not obey the symmetry required in the justification of the GLSM introduced in Audibert-Haddar [Inverse Problems, 2014]. We propose a new formulation by adding an extra penalty term that asymptotically correct the non symmetry of the GLSM original penalty term. The analysis of the new formulation is first presented in an abstract framework. We then show how to apply our setting to the scalar problem with far field measurements or near field measurements on a limited aperture. We finally validate the method through some numerical tests in two dimensions and for far field measurements.

6.1.2. A synoptic approach to the seismic sensing of heterogeneous fractures: from geometric reconstruction to interfacial characterization

B. Guzina, H. Haddar and F. Pourahmadian

A non-iterative waveform sensing approach is proposed toward (i) geometric reconstruction of penetrable fractures, and (ii) quantitative identification of their heterogeneous contact condition by seismic i.e. elastic waves. To this end, the fracture support Γ (which may be non-planar and unconnected) is first recovered without prior knowledge of the interfacial condition by way of the recently established approaches to non-iterative waveform tomography of heterogeneous fractures, e.g. the methods of generalized linear sampling and topological sensitivity. Given suitable approximation $\widetilde{\Gamma}$ of the fracture geometry, the jump in the displacement field across $\widetilde{\Gamma}$ i.e. the fracture opening displacement (FOD) profile is computed from remote sensory data via a regularized inversion of the boundary integral representation mapping the FOD to remote observations of the scattered field. Thus obtained FOD is then used as input for solving the traction boundary integral equation on $\widetilde{\Gamma}$ for the unknown (linearized) contact parameters. In this study, linear and possibly dissipative interactions between the two faces of a fracture are parameterized in terms of a symmetric, complex-valued matrix K collecting the normal, shear, and mixed-mode coefficients of specific stiffness. To facilitate the high-fidelity inversion for K, a 3-step regularization algorithm is devised to minimize the errors stemming from the inexact geometric reconstruction and FOD recovery. The performance of the inverse solution is illustrated by a set of numerical experiments where a cylindrical fracture, endowed with two example patterns of specific stiffness coefficients, is illuminated by plane waves and reconstructed in terms of its geometry and heterogeneous (dissipative) contact condition.

6.1.3. Sampling methods for reconstructing the geometry of a local perturbation in unknown periodic layers

H. Haddar and T.P Nguyen

The aim of this work is the design and analysis of sampling methods to reconstruct the shape of a local perturbation in a periodic layer from measurements of scattered waves at a fixed frequency. We first introduce the model problem that corresponds with the semi-discretized version of the continous model with respect to the Floquet-Bloch variable. We then present the inverse problem setting where (propagative and evanescent) plane waves are used to illuminate the structure and measurements of the scattered wave at a parallel plane to the periodicity directions are performed. We introduce the near field operator and analyze two possible factorizations of this operator. We then establish sampling methods to identify the defect and the periodic background geometry from this operator measurement. We also show how one can recover the geometry of the background independently from the defect. We then introduce and analyze the single Floquet-Bloch mode measurement operators and show how one can exploit them to built an indicator function of the defect independently from the background geometry. Numerical validating results are provided for simple and complex backgrounds.

6.1.4. Nanoparticles volume determination from SAXS measurements

M. Bakry and H. Haddar

The aim of this work is to develop a fully automatic method for the reconstruction of the volume distribution of polydisperse non-interacting nanoparticles with identical shapes from Small Angle X-ray Scattering measurements. In the case of diluted systems we proposed a method that solves a maximum likelihood problem with a positivity constraint on the solution by means of an Expectation Maximization iterative scheme coupled with a robust stopping criterion. We prove that the stopping rule provides a regularization method according to an innovative notion of regularization specifically defined for inverse problems with Poisson data. Such a regularization, together with the positivity constraint results in high fidelity quantitative reconstructions of particle volume distributions making the method particularly effective in real applications. We tested the performance of the method on synthetic data in the case of uni- and bi-modal particle volume distributions. We extended the method to the case of dense solutions where the inverse problem becomes non linear. The developement of this research topic is ongoing under the framework of Saxsize.

6.1.5. Identification of small objects with near-field data in quasi-backscattering configurations

H. Haddar and M. Lakhal

We present a new sampling method for detecting targets (small inclusions or defects) immersed in a homogeneous medium in three-dimensional space, from measurements of acoustic scattered fields created by point source incident waves. We consider the harmonic regime and a data setting that corresponds with quasi-backscattering configuration: the data is collected by a set a receivers that are distributed on a segment centered at the source position and the device is swept along a path orthogonal to the receiver line. We assume that the aperture of the receivers is small compared with the distance to the targets. Considering the asymptotic form of the scattered field as the size of the targets goes to zero and the small aperture approximation, one is able to derive a special expression for the scattered field. In this expression a separation of the dependence of scattered field on the source location and the distance source-target is performed. This allows us to propose a sampling procedure that characterizes the targets location in terms of the range of a near-field operator constructed from available data. Our procedure is similar to the one proposed by Haddar-Rezac for far-field configurations. The reconstruction algorithm is based on the MUSIC (Multiple SIgnal Classification) algorithm.

6.2. Invisiblity and transmission eigenvalues

6.2.1. Trapped modes and reflectionless modes as eigenfunctions of the same spectral problem

A.-S. Bonnet-Ben Dhia, L. Chesnel and V. Pagneux

We consider the reflection-transmission problem in a waveguide with obstacle. At certain frequencies, for some incident waves, intensity is perfectly transmitted and the reflected field decays exponentially at infinity. We show that such reflectionless modes can be characterized as eigenfunctions of an original non-selfadjoint spectral problem. In order to select ingoing waves on one side of the obstacle and outgoing waves on the other side, we use complex scalings (or Perfectly Matched Layers) with imaginary parts of different signs. We prove that the real eigenvalues of the obtained spectrum correspond either to trapped modes (or bound states in the continuum) or to reflectionless modes. Interestingly, complex eigenvalues also contain useful information on weak reflection cases. When the geometry has certain symmetries, the new spectral problem enters the class of $\mathcal{PT}$-symmetric problems.

6.2.2. Transmission eigenvalues with artificial background for explicit material index identification

L. Audibert, L. Chesnel and H. Haddar

We are interested in the problem of retrieving information on the refractive index n of a penetrable inclusion embedded in a reference medium from farfield data associated with incident plane waves. Our approach relies on the use of transmission eigenvalues (TEs) that carry information on n and that can be determined from the knowledge of the farfield operator F. We explain how to modify F into a farfield operator $F^{\mathrm{a}} = F - \widetilde{F}$, where $\widetilde{F}$ is computed numerically, corresponding to well chosen artificial background and for which the associated TEs provide more accessible information on n.

6.2.3. Simple examples of perfectly invisible and trapped modes in waveguides

L. Chesnel and V. Pagneux

We consider the propagation of waves in a waveguide with Neumann boundary conditions. We work at low wavenumber focusing our attention on the monomode regime. We assume that the waveguide is symmetric with respect to an axis orthogonal to the longitudinal direction and is endowed with a branch of height L whose width coincides with the wavelength of the propagating modes. In this setting, tuning the parameter L, we prove the existence of simple geometries where the transmission coefficient is equal to one (perfect invisibility). We also show that these geometries, for possibly different values of L, support so called trapped modes (non zero solutions of finite energy of the homogeneous problem) associated with eigenvalues embedded in the continuous spectrum.

6.2.4. Invisibility and perfect reflectivity in waveguides with finite length branches

L. Chesnel, S.A. Nazarov and V. Pagneux

We consider a time-harmonic wave problem, appearing for example in water-waves theory, in acoustics or in electromagnetism, in a setting such that the analysis reduces to the study of a 2D waveguide problem with a Neumann boundary condition. The geometry is symmetric with respect to an axis orthogonal to the direction of propagation of waves. Moreover, the waveguide contains one branch of finite length. We analyse the behaviour of the complex scattering coefficients $\mathcal{R}$, $\mathcal{T}$ as the length of the branch increases and we exhibit situations where non reflectivity ($\mathcal{R} = 0$, $|\mathcal{T}| = 1$), perfect reflectivity ($|\mathcal{R}| = 1$, $\mathcal{T} = 0$) or perfect invisibility ($\mathcal{R} = 0$, $\mathcal{T} = 1$) hold. Numerical experiments illustrate the different results.

6.2.5. Invisibility in scattering theory

L. Chesnel, A.-S. Bonnet-Ben Dhia and S.A. Nazarov

We are interested in a time harmonic acoustic problem in a waveguide with locally perturbed sound hard walls. We consider a setting where an observer generates incident plane waves at $-\infty$ and probes the resulting scattered field at $-\infty$ and $+\infty$. Practically, this is equivalent to measure the reflection and transmission coefficients respectively denoted R and T. In a recent work, a technique has been proposed to construct waveguides with smooth walls such that $R = 0$ and $|T| = 1$ (non reflection). However the approach fails to ensure $T = 1$ (perfect transmission without phase shift). First we establish a result explaining this observation. More precisely, we prove that for wavenumbers smaller than a given bound $k_{☆}$ depending on the geometry, we cannot have $T = 1$ so that the observer can detect the presence of the defect if he/she is able to measure the phase at $+\infty$. In particular, if the perturbation is smooth and small (in amplitude and in width), $k_{☆}$ is very close to the threshold wavenumber. Then, in a second step, we change the point of view and, for a given wavenumber, working with singular perturbations of the domain, we show how to obtain $T = 1$. In this case, the scattered field is exponentially decaying both at $-\infty$ and $+\infty$. We implement numerically the method to provide examples of such undetectable defects.

6.2.6. New sets of eigenvalues in inverse scattering for inhomogeneous media and their determination from scattering data

F. Cakoni, H. Haddar and L. Audibert

We developed a general mathematical framework to determine interior eigenvalues from a knowledge of the modified far field operator associated with an unknown (anisotropic) inhomogeneity. The modified far field operator is obtained by subtracting from the measured far field operator the computed far field operator corresponding to a well-posed scattering problem depending on one (possibly complex) parameter. Injectivity of this modified far field operator is related to an appropriate eigenvalue problem whose eigenvalues can be determined from the scattering data, and thus can be used to obtain information about material properties of the unknown inhomogeneity. We discuss here two examples of such modification leading to a Steklov eigenvalue problem, and a new type of the transmission eigenvalue problem. We present some numerical examples demonstrating the viability of our method for determining the interior eigenvalues form far field data.

6.2.7. The Asymptotic of Transmission Eigenvalues for a Domain with a Thin Coating

H. Boujlida, H Haddar and M. Khenissi

We consider the transmission eigenvalue problem for a medium surrounded by a thin layer of inhomogeneous material with different refractive index. We derive explicit asymptotic expansion for the transmission eigenvalues with respect to the thickness of the thin layer. We prove error estimate for the asymptotic expansion up to order 1 for simple eigenvalues. This expansion can be used to obtain explicit expressions for constant index of refraction.

6.3. Shape and topology optimization

6.3.1. Structural optimization under overhang constraints imposed by additive manufacturing technologies

G. Allaire, C. Dapogny, R. Estevez, A. Faure and G. Michailidis.

This work addresses one of the major constraints imposed by additive manufacturing processes on shape optimization problems - that of overhangs, i.e. large regions hanging over void without sufficient support from the lower structure. After revisiting the ‘classical’ geometric criteria used in the literature, based on the angle between the structural boundary and the build direction, we propose a new mechanical constraint functional, which mimics the layer by layer construction process featured by additive manufacturing technologies, and thereby appeals to the physical origin of the difficulties caused by overhangs. This constraint, as well as some variants, are precisely defined; their shape derivatives are computed in the sense of Hadamard’s method, and numerical strategies are extensively discussed, in two and three space dimensions, to efficiently deal with the appearance of overhang features in the course of shape optimization processes.

6.3.2. Shape optimisation with the level set method for contact problems in linearised elasticity

G. Allaire, F. Jouve and A. Maury

This work is devoted to shape optimisation of contact problems in linearised elasticity, thanks to the level set method. We circumvent the shape non-differentiability, due to the contact boundary conditions, by using penalised and regularised versions of the mechanical problem. This approach is applied to five different contact models: the frictionless model, the Tresca model, the Coulomb model, the normal compliance model and the Norton-Hoff model. We consider two types of optimisation problems in our applications: first, we minimise volume under a compliance constraint, second, we optimise the normal force, with a volume constraint, which is useful to design compliant mechanisms. To illustrate the validity of the method, 2D and 3D examples are performed, the 3D examples being computed with an industrial software.

6.3.3. Elasto-plastic shape optimization using the level set method

G. Allaire, F. Jouve and A. Maury

This work is concerned with shape optimization of structures made of a material obeying Hencky's laws of plasticity, with the stress bound expressed by the von Mises effective stress. The ill-posedness of the model is circumvented by using two regularized versions of the mechanical problem. The first one is the classical Perzyna formulation which is regularized, the second one is a new regularized formulation proposed for the von Mises criterion. Shape gradients are calculated thanks to the adjoint method. The optimal shape is numerically computed by using the level set method. To illustrate the validity of the method, 2D examples are performed.

6.4. Numerical methods for wave problems

6.4.1. Finite element methods for eigenvalue problems with sign-changing coefficients

C. Carvalho, P. Ciarlet and L. Chesnel

We consider a class of eigenvalue problems involving coefficients changing sign on the domain of interest. We analyse the main spectral properties of these problems according to the features of the coefficients. Under some assumptions on the mesh, we study how one can use classical finite element methods to approximate the spectrum as well as the eigenfunctions while avoiding spurious modes. We also prove localisation results of the eigenfunctions for certain sets of coefficients.

6.4.2. Linearized Navier-Stokes equations for Aeroacoustics using Stabilized Finite Elements : Boundary Conditions and Industrial Application to Aft-Fan Noise Propagation.

A. Bissuel, G. Allaire, L. Daumas, S., Barré and F. Rey

A numerical method for solving the linearized Navier-Stokes equations is presented for aeroacoustic sound propagation problem. The Navier-Stokes equations are linearized in the frequency domain. The fan noise of jet engine is emitted nearly selectively on some frequencies, which depend on the rotation velocity of the fan. A frequency domain approach is highly suitable for this kind of problems, instead of a costly time-dependent simulation which can handle a large range of frequencies depending on the time step and the mesh. The calculations presented here were all made using Aether, a Navier- Stokes code which uses finite elements stabilized with SUPG (Streamline Upwind Galerkin). Automatic code differentiation was used to linearize this code. Entropy variables bring interesting mathematical properties to the numerical scheme, but also prevent the easy implementation of boundary conditions. For instance, the pressure is a non-linear combination of the entropy variables. Imposing a pressure variation needs a linearization of this relation which is detailed herein. The performance of different types of boundary conditions used to impose the acoustic pressure variation inside the engine is studied in detail. Finally, a very surprising effect of the SUPG scheme was to transform a homogeneous Dirichlet boundary condition on all variables to a transparent one which is able to let only outgoing waves pass through with no incoming wave. A one-dimensional toy model is given to explain how SUPG brings about this transformation.

We finally treated an industrial test case. The geometry of a model turbine from the Clean Sky European project was used for sound propagation of the fan exhaust noise of a jet engine. Computations on several modes with increasing complexities were done and the results compared to a boundary element method which served as a reference when no mean flow is present. Results of a computation with a mean flow are shown.

6.5. Diffusion MRI

J.R. Li, K. V. Nguyen and I. Mekkaoui

Diffusion Magnetic Resonance Imaging (DMRI) is a promising tool to obtain useful information on microscopic structure and has been extensively applied to biological tissues.

We obtained the following results.

- The Bloch-Torrey equation describes the evolution of the spin (usually water proton) magnetization under the influence of applied magnetic field gradients and is commonly used in numerical simulations for diffusion MRI and NMR. Microscopic heterogeneity inside the imaging voxel is modeled by interfaces in- side the simulation domain, where a discontinuity in the magnetization across the interfaces is produced via a permeability coefficient on the interfaces. To avoid having to simulate on a computational domain that is the size of an en- tire imaging voxel, which is often much larger than the scale of the microscopic heterogeneity as well as the mean spin diffusion displacement, smaller represen- tative volumes of the imaging medium can be used as the simulation domain. In this case, the exterior boundaries of a representative volume either must be far away from the initial positions of the spins or suitable boundary conditions must be found to allow the movement of spins across these exterior boundaries.

  Many approaches have been taken to solve the Bloch-Torrey equation but an efficient high performance computing framework is still missing. We present formulations of the interface as well as the exterior boundary conditions that are computationally efficient and suitable for arbitrary order finite elements and parallelization. In particular, the formulations use extended finite elements with weak enforcement of real (in the case of interior interfaces) and artificial (in the case of exterior boundaries) permeability conditions as well as operator splitting for the exterior boundary conditions. The method is straightforward to implement and it is available in the FEniCS for moderate-scale simulations and in the FEniCS-HPC for large-scale simulations.
- The nerve cells of the *Aplysia* are much larger than mammalian neurons. Using the *Aplysia* ganglia to study the relationship between the cellular structure and the diffusion MRI signal can potentially shed light on this relationship for more complex organisms. We measured the dMRI signal of chemically-fixed abdominal ganglia of the *Aplysia* at several diffusion times. At the diffusion times measured, the dMRI signal is mono-exponential and can be accurately represented by the parameter ADC.

  We analyzed the diffusion time-dependent ADC using a well-known analytical formula that is valid in the short diffusion time regime. We performed this analysis for the largest sized cells of the ganglia to satisfy the short diffusion time requirement. We noted that a naive application of the short time formula is not adequate because of the presence of the cell nucleus, making the effective cell size much smaller than the actual cell size.

  We went on to perform numerical simulation of the ADC for several cell types of the abdominal ganglia. To create the simulation geometries, for the largest cells, we segmented a high resolution T2-weighted images and incorporated a manually generated nucleus. For small cells and nerve cells, we created spherical and cylindrical geometrical domains that are consistent with known information about the cellular structures from the literature. Using the library of simulation results, we fitted for the intrinsic diffusivities of the small cells and the nerve cells.
- We participated in providing simulation results for the Parietal team in their work on sensing Spindle Neurons in the Insula with Multi-shell Diffusion MRI.

- We started a new direction in the simulation and modeling of heart diffusion MRI with the post-doc project of Imen Mekkaoui, funded by Inria-EPFL lab. The project is co-supervised with Jan Hesthaven, Chair of Computational Mathematics and Simulation Science (MCSS), EPFL.

6.6. Mathematical tools for Psychology

J. R. Li and J. Hao

This is the start of a collaborative effort between the Defi team and the mental health professionals at the centre hospitalier Sainte Anne and l'Université Paris Diderot.

- We started a new research direction in algorithm and software development for analysis and classification of EEG measurements during the administration of neuropsychological tests for AD/HD with the PhD project of Jingjing Hao, co-supervised with Dr. Hassan Rahioui, Chef du pôle psychiatrique du 7e arrondissement de Paris rattaché au centre hospitalier Sainte-Anne.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- A CIFRE PhD thesis started January 2015 with Dassault Aviations. The student is M. Aloïs Bissuel who is working on "linearized Navier-Stokes equations for optimization, fluttering and aeroacoustic".
- A CIFRE PhD thesis started December 2015 with Safran Tech. The student is Mrs Perle Geoffroy who is working on "topology optimization by the homogenization method in the context of additive manufacturing".
- A CIFRE PhD thesis started April 2017 with Safran Tech. The student is M. Florian Feppon who is working on "topology optimization for a coupled thermal-fluid-structure system".
- A CIFRE PhD thesis started October 2017 with Renault. The student is Mrs Lalaina Rakotondrainibe who is working on "topology optimization of connections between mechanical parts".
- A CIFRE PhD thesis started November 2017 with EDF. The student is H. Girardon who is working on "level set method for eddy current non destructive testting".

7.2. Bilateral Grants with Industry

- The SOFIA project (SOlutions pour la Fabrication Industrielle Additive métallique) started in the summer of 2016. Its purpose is to make research in the field of metallic additive manufacturing. The industrial partners include Michelin, FMAS, ESI, Safran and others. The academic partners are different laboratories of CNRS, including CMAP at Ecole Polytechnique. The project is funded for 6 years by BPI (Banque Publique d'Investissement).
- G. Allaire is participating to the TOP project at IRT SystemX which started in February 2017. It is concerned with the development of a topology optimization platform with industrial partners (Renault, Safran, Airbus, ESI).
- FUI project Tandem. This three years project started in December 2012 and has been extended to September 2017 involves Bull-Amesys (coordinator), BOWEN (ERTE+SART), Ecole Polytechnique (CMAP), Inria, LEAT et VSM. It aims at constructing a radar system on a flying device capable of real-time imaging mines embedded in dry soils (up to 40 cm deep). We are in charge of numerical validation of the inverse simulator.
- FUI project Saxsize. This three years project started in October 2015 and involves Xenocs (coordinator), Inria (DEFI), Pyxalis, LNE, Cordouan and CEA. It is a followup of Nanolytix where a focus is put on SAXS quantifications of dense nanoparticle solutions.

8. Partnerships and Cooperations

8.1. International Initiatives

8.1.1. Participation in Other International Programs

8.1.1.1. International Initiatives

QUASI

Title: Qualitative Approaches to Scattering and Imaging

International Partner (Institution - Laboratory - Researcher):

University of Rutgers (United States) - Fioralba Cakoni

Duration: 2013 - 2017

Start year: 2013

We concentrate on the use of qualitative methods in acoustic and electromagnetic inverse scattering theory with applications to nondestructive evaluation of materials and medical imaging. In particular, we would like to address theoretical and numerical reconstruction techniques to solve the inverse scattering problems using either time harmonic or time dependent measurements of the scattered field. The main goal of research in this field is to not only detect but also identify geometric and physical properties of unknown objects in real time.

8.2. International Research Visitors

8.2.1. Visits of International Scientists

- Fioralba Cakoni (2 weeks)
- David Colton (1 week)
- Armin Lechleiter (1 week)
- Rainer Kress (1 week)

8.2.1.1. Internships

- Marwa Kchaou (ENIT) 6 months
- FatmeMustapha (EDF) 6 months
- DucVu (Inria) 3 months

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

- G. Allaire is a member of the "comité national" CNRS, section 41 (mathematics). He is a member of the board of the Gaspard Monge program on optimization (PGMO) at the Jacques Hadamard Mathematical Foundation. He is a board member of Institut Henri Poincaré (IHP). He is the chairman of the scientific council of IFPEN (French Petroleum Institute and New Energies).
- L. Chesnel co-organized the Journée de rentrée (2017) of the Centre de Mathématiques Appliquées of École Polytechnique
- L. Chesnel co-organize the seminar of the Centre de Mathématiques Appliquées of École Polytechnique and the joint seminar of the Inria teams Defi-M3DISIM-Poems.

- H. Haddar Co-organized of the third Franco-German Summer School “Inverse Problems and Imaging”, University of Bremen, September 18-22, 2017
- DEFI was a sponsor of the conference "Waves diffracted by Patrick Joly", Paris, 2017.
- J.R. Li is organizer of Ecole d’ete d’excellence for Chinese Master’s students funded by French Embassy in China, 2017.
- J.R. Li is member of Organizing Committee of SIAM Conference on Computational Science and Engineering, 2017

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- J.R. Li is member of the SIAM Committee on Programs and Conferences 2017-2019
- J.R. Li is responsable for the Ecole Polytechnique part of the French-Vietnam Master Program in Applied Mathematics, 2017
- J.R. Li is reviewer for Millennium Science Initiative, a program of the Government of Chile, 2017.
- H. Haddar is member of the scientific committees of the conferences series TAMTAM, Picof and Waves

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- G. Allaire is member of the editorial board of
  - book series "Mathématiques et Applications" of SMAI and Springer,
  - ESAIM/COCV, Structural and Multidisciplinary Optimization,
  - Discrete and Continuous Dynamical Systems Series B,
  - Computational and Applied Mathematics,
  - Mathematical Models and Methods in Applied Sciences (M3AS),
  - Annali dell’Universita di Ferrara,
  - OGST (Oil and Gas Science and Technology),
  - Journal de l’Ecole Polytechnique - Mathématiques,
  - Journal of Optimization Theory and Applications.
- H. Haddar is
  - member the editorial advisory board of Inverse Problems
  - Associate Editor of the SIAM Journal on Scientific Computing
  - Guest editor of Computers and Mathematics with Applications for a special issue on "Numerical Methods for PDEs and Inverse Problems"

9.1.3.2. Reviewer - Reviewing Activities

The members of the team reviewed numerous papers for numerous international journals. Too many to make a list.

9.1.4. Invited Talks

- G. Allaire
  - "GAMM-Seminar on Microstructures", Dortmund (January 2017).
  - Workshop on "Shape, Images and Optimization", Münster (March 2017).
  - Interaction of Applied Mathematics and Mechanics Conference, IAMMC2017, Paris (May 2017).
  - Congrès CSMA, Giens (May 2017).
  - New trends in shape optimization, Vosges (May 2017).
  - WCSMO, Braunschweig (June 2017).
  - CEDYA, Cartagena (June 2017).
  - Waves diffracted by Patrick Joly, Gif-sur-Yvette (August 2017).
  - SIM-AM ECCOMAS conference, Münich (October 2017).
- L. Chesnel
  - Worshop Inverse plasmonic problems-Neumann Poincaré operator, Université de Grenoble-Alpes, November 2017.
  - Séminaire EDP, modélisation et calcul scientifique, UMPA, ENS Lyon, November 2017.
  - Séminaire EDP, analyse et applications, Université de Lorraine, Metz, November 2017.
  - Séminaire EDP/Physique mathématique, Université de Bordeaux, September 2017.
  - Waves diffracted by Patrick Joly, Gif-sur-Yvette, August 2017.
- H. Haddar
  - TamTam'17, Hammamet, Tunisia, May 2017, Minisymposium, Inverse and imaging problems for PDE with applications
  - Oberwolfach Workshop Computational Inverse Problems for Partial Differential Equations, Oberwolfach, May 2017.
  - Workshop on the occasion of the 75th birthday of Rainer Kress, Goettingen, May 2017
  - Applied Inverse Problems, Hangzou, May 2017
    - Minisymposium on Inverse Spectral Problems
    - Minisymposium on Stability and reconstruction in inverse problems and their applications
    - Minisymposium on Recent Developments on Computation of Transmission Eigenvalues with Applications
  - Workshop on nonlinear analysis : Recent advances and new trends, Monastir, July 2017
  - Quantitative Tomographic Imaging : Radon meets Bell and Maxwell, RICAM, Linz, July 2017
  - Waves diffracted by Patrick Joly, Gif-sur-Yvette, August 2017.
  - Colloquium of the mathematical department, Mainz University, October 2017.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- Master : Grégoire Allaire, Approximation Numérique et Optimisation, for students in the second year of Ecole Polytechnique curriculum: 8 lessons of 1h30.
- Master : Houssem Haddar, Approximation Numérique et Optimisation, for students in the second year of Ecole Polytechnique curriculum: 8 TDs of 4h.

- Master : Houssem Haddar, Variational analysis of partial differential equations, for students in the second year of Ecole Polytechnique curriculum: 8 TDs of 4h.
- Master : Lucas Chesnel, "Variational analysis for partial differential equations", 16 equivalent TD hours, second year (2A), École Polytechnique, Palaiseau, France
- Master : Lucas Chesnel, "Numerical approximation and optimisation", 14 equivalent TD hours, second year (2A), École Polytechnique, Palaiseau, France
- Master : Lucas Chesnel, "Elementary tools of analysis for partial differential equations", 25 equivalent TD hours, L3, Ensta ParisTech, Palaiseau, France
- Master : Grégoire Allaire, Optimal design of structures, for students in the third year of Ecole Polytechnique curriculum. 9 lessons of 1h30.
- Master : Grégoire Allaire, Theoretical and numerical analysis of hyperbolic systems of conservation laws, Master M2 "mathematical modeling", 8 lessons of 3h.
- Master : Jing Rebecca Li, Mathematical and numerical foundations of modeling and simulation using partial differential equations. French-Vietnam Master Program in Applied Mathematics.
- Doctorat : Houssem Haddar, Lecturer at the Summer School on Quantitative Tomographic Imaging : Radon meets Bell and Maxwell. (2x1h30) July 10-14, RICAM, Linz, 2017.

9.2.2. Supervision

- Ph.D. : M. Lakhal, Méthodes d'inversion pour la reconstruction de mines enfouies à partir de mesures d'antennes radar, June 2017, H. Haddar
- Ph.D. : T.P. Nguyen, Direct and inverse solvers for scattering problems from locally perturbed infinite periodic layers, January 2017, H. Haddar
- Ph.D. : K. Van Nguyen, Modeling, simulation and experimental verification of water diffusion in neuronal network of the Aplysia ganglia, March 2017, J.-R. Li and L. Ciobanu
- Ph.D. in progress: B. Charfi, Identification of the sigular support of a GIBC, 2014, H. Haddar and S. Chaabane
- PhD in progress : A. Talpaert, the direct numerical simulation of vapor bubbles at low Mach number with adaptative mesh refinement, 2013, G. Allaire and S. Dellacherie
- PhD in progress : A. Bissuel, linearized Navier Stokes equations for optimization, floating and aeroaccoustic, 2014, G. Allaire
- PhD in progress : P. Geoffroy on topology optimization by the homogenization method in the context of additive manufacturing (Safran Tech, to be defended in 2019), G. Allaire.
- PhD in progress : S. Houbar sur la cavitation dans le fluide caloporteur induite par les mouvements des assemblages d'un réacteur (CEA, to be defended in 2020), G. Allaire and G. Campioni
- PhD in progress : M. Boissier sur l'optimisation couplée de la topologie des formes et de la trajectoire de lasage en fabrication additive (to be defended in 2020). G. Allaire and Ch. Tournier.
- PhD in progress : L. Rakotondrainibe sur l'optimisation des liaisons enre pièces dans les système mécaniques (to be defended in 2020), G. Allaire.
- PhD in progress : F. Feppon sur l'optimisation topologique de systèmes couplés fluide-solide-thermique (Safran, to be defended in 2020), G. allaire and Ch. Dapogny.
- PhD in progress : Q. Feng sur les éléments finis multi-échelles pour Navier Stokes incompressible en milieu encombré (CEA, to be defended in 2019), G. Allaire and A. Cartalade.
- PhD in progress : K. Napal, Transmission eigenvalues and non destructive testing of concrete like materials , 2016, L. Chesnel H. Haddar and L. Audibert
- PhD in progress : M. Kchaou, Higher order homogenization tensors for DMRI modeling, 2016, H. Haddar, J.R Li and M. Moakher

- PhD in progress : H. Girardon, Non destructive testing of PWR tubes using eddy current rotating coils, 2017, H. Haddar and L. Audibert
- PhD in progress : J. Hao, Thesis topic: Algorithm and software development for analysis and classification of EEG measurements during administration of neuropsychological tests for AD/HD, 2017, J.R. Li and H. Rahioui.

10. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journals

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[2] L. AUDIBERT, F. CAKONI, H. HADDAR. *New sets of eigenvalues in inverse scattering for inhomogeneous media and their determination from scattering data*, in "Inverse Problems", December 2017, vol. 33, n° 12, pp. 1-30 [*DOI :* 10.1088/1361-6420/AA982F], https://hal.inria.fr/hal-01645862

[3] L. AUDIBERT, H. HADDAR. *The Generalized Linear Sampling Method for limited aperture measurements*, in "SIAM Journal on Imaging Sciences", 2017, vol. 10, n° 2, pp. 845–870 [*DOI :* 10.1137/16M110112X], https://hal.archives-ouvertes.fr/hal-01422027

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[20] L. CHESNEL, V. PAGNEUX. *Simple examples of perfectly invisible and trapped modes in waveguides*, September 2017, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01593226

[21] M. GIACOMINI, O. PANTZ, K. TRABELSI. *Volumetric expressions of the shape gradient of the compliance in structural shape optimization*, January 2017, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01441943

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