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Project-Team DEFI

Shape reconstruction and identification

IN COLLABORATION WITH: Centre de Mathématiques Appliquées (CMAP)

RESEARCH CENTER
Saclay - Île-de-France

THEME
Computational models and simulation

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Project-Team DEFI

Keywords: Inverse Problem, Scientific Computation, Shape Optimization, Waves, Medical Images

Our EPI is located at the Center of Applied Mathematics (CMAP), Ecole Polytechnique.

Creation of the Project-Team: January 01, 2009 .

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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.

2.2. Highlights of the Year

- Grégoire Allaire was elected as president of SMAI.

3. Scientific Foundations

3.1. Scientific Foundations

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 shall 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 a universal satisfactory solution to it (regarding 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, echography, X-ray tomography, etc.), that rely on one of these approximations.

Generally speaking, the used simplifications result in a linearization of the inverse problem and therefore are usually valid only if the latter is weakly non-linear. The development of these 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 spaced 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 will be motivated and inspired by recent advances in shape and topological optimization methods and also the introduction of novel classes of imaging algorithms, so-called sampling methods.

The 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 of 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 constraint 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 of 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 build 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 from 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 grayscale 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, and 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 is 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 showing 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 coefficient D will appear as the slope of the semi-log plot of the signal (in appropriate 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. Software

5.1. RODIN

Participant: Grégoire Allaire [correspondant].

RODIN project: developing an industrial software for geometry and topology optimization of solid structures, based on the level set method.

5.2. FreeFem++ Toolboxes

5.2.1. Shape optimization toolbox in FreeFem++

Participants: Grégoire Allaire, Olivier Pantz.

We propose several FreeFem++ routines which allow the users to optimize the thickness, the geometry or the topology of elastic structures. All examples are programmed in two space dimensions. These routines have been written by G. Allaire, B. Boutin, C. Dousset, O. Pantz. A web page of this toolbox is available at http://www.cmap.polytechnique.fr/~allaire/freefem_en.html.

We also have written a C++ code to solve the Hamilton Jacoby equation used in the Level-set shape optimization method. This code has been linked with FreeFem++ routines.

5.2.2. *Inverse shape and medium problem for thin coatings*

Participant: Nicolas Chaulet.

We developed a FreeFem++ toolbox which retrieve an obstacle and two coefficients that define a generalized impedance boundary condition from a few far field data in dimension 2. The reconstruction algorithm relies on regularized non linear optimization technique. The toolbox also contains a forward solver for the scattering of acoustic waves by obstacle on which a generalized impedance boundary condition is applied using an approximate Dirichlet-to-Neuman map to bound the computational domain.

5.2.3. *Inverse shape problems for axisymmetric eddy current problems*

Participant: Zixian Jiang.

This FreeFem++ toolbox solves inverse problems for an axisymmetric eddy current model using shape optimization techniques. The underlying problem is to find inclusions in a tubular and unbounded domain. The direct scattering problems are solved using an adaptive finite element method, and Dirichlet-to-Neumann operators are used to implement the transparent boundary conditions. Based on the shape derivative of an inclusion with respect to the domain, the toolbox offers regularized iterative algorithms to solve the inverse problem.

5.2.4. *Contact managements*

Participant: Olivier Pantz.

We have developed a toolbox running under Freefem++ in order to take into account the non-intersection constraints between several deformable bodies. This code has been used to treat contacts between red blood cells in our simulations, but also between genuine non linear elastic structure. It can handle both contacts and self-contacts.

Moreover, a toolbox based on the Penalization method has also been developed.

5.2.5. *De-Homogenization*

Participant: Olivier Pantz.

We have developed a code under Freefem++ that implements our De-Homogenization method. It has been used to solve the compliance minimization problem of the compliance of an elastic shape. In particular, it enables us to recover well known optimal Michell's trusses for shapes of low density.

5.3. Scilab and Matlab Toolboxes

5.3.1. *Shape optimization toolbox in Scilab*

Participant: Grégoire Allaire [correspondant].

Together with Georgios Michailidis, we improved a Scilab toolbox for 2-d shape and topology optimization by the level set method which was originally produced by Anton Karrman and myself. The routines, a short user's manual and several examples are available on the web page: http://www.cmap.polytechnique.fr/~allaire/levelset_en.html

5.3.2. *Conformal mapping method*

Participant: Housseem Haddar [correspondant].

This Scilab toolbox is dedicated to the resolution of inverse 2-D electrostatic problems using the conformal mapping method introduced by Akdumann, Kress and Haddar. The toolbox treats the cases of a simply connected obstacle with Dirichlet, Neumann or impedance boundary conditions or a simply connected inclusion with a constant conductivity. The latest development includes the extension of the method to the inverse scattering problem at low frequencies as introduced by Haddar-Kress (2012).

5.3.3. *Direct and inverse problems in waveguides*

Participants: Armin Lechleiter [correspondant], Dinh Liem Nguyen.

This Matlab toolbox includes fast solvers for direct and inverse scattering problems in planar 3D waveguides for inhomogeneous media. The direct scattering problems are solved using an spectral integral equation approach relying on the Lippmann-Schwinger integral equation, discretized as a Galerkin method via the fast Fourier transform. The toolbox includes preconditioning by a two-grid scheme and multipole expansions coupled to the spectral solver to allow for multiple scattering objects. The inverse problem to find the shape of the scattering object from near-field measurements is solved using a Factorization method.

5.4. Sampling methods for inverse problems

5.4.1. *Samplings-2d*

Participant: Housseem Haddar [correspondant].

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

See also the web page <http://sourceforge.net/projects/samplings-2d/>.

- License: GPL
- Type of human computer interaction: sourceforge
- OS/Middleware: Linux
- Programming language: Fortran
- Documentation: fichier

5.4.2. *Samplings-3d*

Participant: Housseem Haddar [correspondant].

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.

5.4.3. *Time domain samplings-2d*

Participants: Housseem Haddar [correspondant], Armin Lechleiter.

This software is written in Fortran 90 and is related to forward and inverse problems for the time dependent wave equation in 2-D. The forward solver is based on a FDTD method with PMLs. The inverse part is an implementation of the linear sampling method in a near field setting and the factorization method in a far field setting.

5.4.4. *Factorization Method for EIT*

Participant: Giovanni Migliorati.

We developed a numerical code that implements the Factorization Method applied to the Continuous Model, in the framework of Electrical Impedance Tomography featuring an inhomogeneous background. The numerical scheme relies on the approximation by the finite element method of the solution to the dipole-like Neumann boundary-value problem. Two regularization techniques are implemented, i.e. the Tikhonov regularization embedding Morozov principle, and the classical Picard Criterion. The code now supports the case of piecewise-wise constant by unknown background.

5.5. BlochTorreyPDESolver

Participants: Jing-Rebecca Li [correspondant], Dang Van Nguyen.

We developed numerical codes to solve the multiple compartment Bloch Torrey partial differential equation in 2D and 3D to simulate the bulk magnetization of a sample under the influence of a diffusion-encoding gradient magnetic field. We coupled a mass-conserving spatial discretization with a stable time discretization using an explicit Runge-Kutta-Chebyshev method and we are able to solve the Bloch-Torrey PDE in multiple compartments for an arbitrary diffusion sequence with reasonable accuracy for moderately complicated geometries in computational time that is on the order of tens of minutes per bvalue on a laptop computer.

This code has been implemented in Fortran90, C++, as well as Matlab. A Matlab Toolbox with graphical user interface for the simulation of DMRI signals in 2D and 3D cellular geometries using this numerical method is being developed.

The version of the code using Finite Volume discretization on a Cartesian grid is complete (written by Jing-Rebecca Li). The version of the code using linear Finite Elements discretization is in the final testing phase (written by Dang Van Nguyen)

See the web page <http://www.cmap.polytechnique.fr/~jingrebeccali/> for more details.

6. New Results

6.1. Qualitative methods for inverse scattering problems

6.1.1. Sampling methods with time dependent data

Participant: Housseem Haddar.

Together with A. Lechleiter and S. Marmorat we proposed and analyzed a time domain linear sampling method as an algorithm to solve the inverse scattering problem of reconstructing an obstacle with Robin or Neumann boundary condition from time-dependent near-field measurements of scattered waves. Our algorithm is based on our earlier work to solve a similar inverse scattering problem for obstacles with Dirichlet boundary conditions. In addition to the analysis of a different scattering problem, we provided a substantial improvement of the method on both theoretical and numerical levels. More specifically, we analyzed the method for incident waves generated by pulses with bounded spectrum. Moreover, adapting the function space setting to this type of data allowed us to provide a simpler analysis. On the numerical side, we presented a fast implementation of the inversion algorithm that relies on a FFT-based evaluation of the near-field operator [34].

6.1.2. Inverse problems for periodic penetrable media

Participant: Dinh Liem Nguyen.

Imaging periodic penetrable scattering objects is of interest for non-destructive testing of photonic devices. The problem is motivated by the decreasing size of periodic structures in photonic devices, together with an increasing demand in fast non-destructive testing. In this project, we considered the problem of imaging a periodic penetrable structure from measurements of scattered electromagnetic waves. As a continuation of earlier work jointly with A. Lechleiter [24], [25], [23], we considered an electromagnetic problem for transverse magnetic waves (previous work treats transverse electric fields), and also the full Maxwell equations. In both cases, we treat the direct problem by a volumetric integral equation approach and construct a Factorization method [4], [44], [43], [48].

6.1.3. *Transmission Eigenvalues and their application to the identification problem*

Participant: Housseem Haddar.

The so-called interior transmission problem plays an important role in the study of inverse scattering problems from (anisotropic) inhomogeneities. Solutions to this problem associated with singular sources can be used for instance to establish uniqueness for the imaging of anisotropic inclusions from multi-static data at a fixed frequency. It is also well known that the injectivity of the far field operator used in sampling methods is related to the uniqueness of solutions to this problem. The frequencies for which this uniqueness fails are called transmission eigenvalues. We are currently developing approaches where these frequencies can be used in identifying (qualitative information on) the medium properties. Our research on this topic is mainly done in the framework of the associate team ISIP <http://www-direction.inria.fr/international/PHP/Networks/LiEA.php> with the University of Delaware. A review article on the state of art concerning the transmission eigenvalue problem has been written in collaboration with F. Cakoni [32]. We are also in the process of editing a special issue of the journal *Inverse Problems* dedicated to the use of these transmission eigenvalues in inverse problems. Our recent contributions are the following:

- In collaboration with M. Fares and F. Collino from CERFACS and A. Cossonnière from ENSIEETA we finalized our work on the use of a surface integral equation approach to numerically compute transmission eigenvalues for inclusions with piecewise constant index. The main difficulty behind this procedure is the compactness of the obtained integral operator in usual Sobolev spaces associated with the forward scattering problem. We solved this difficulty by introducing a preconditioning operator associated with a “coercive” transmission problem. On the theoretical side, together with A. Cossonnière we also finalized the analysis of the Fredholm properties of the interior transmission problem for the cases where the index contrast changes sign outside the boundary by using the surface integral equation approach [16].
- With G. Giorgi, we developed a method that give estimates on the material properties using the first transmission eigenvalue. This method is based on reformulating the interior transmission eigenvalue problem into an eigenvalue problem for the material coefficients. We validated our methodology for homogeneous and inhomogeneous inclusions and backgrounds. We also treated the case of a background with absorption and the case of scatterers with multiple connected components of different refractive indexes [21].
- With F. Cakoni and D. Colton we initiated the study of transmission eigenvalues for absorbing media. In particular, we showed that, in the case of absorbing media, transmission eigenvalues form a discrete set, exist for sufficiently small absorption and for spherically stratified media exist without this assumption. For constant index of refraction, we also obtained regions in the complex plane where the transmission eigenvalues cannot exist and obtain a priori estimates for real transmission eigenvalues [14].
- With F. Cakoni and A. Cossonnière we considered the interior transmission problem corresponding to the inverse scattering by an inhomogeneous (possibly anisotropic) media in which an impenetrable obstacle with Dirichlet boundary conditions is embedded. Our main focus is to understand the associated eigenvalue problem, more specifically to prove that the transmission eigenvalues form a discrete set and show that they exist. The presence of Dirichlet obstacle brings new difficulties to already complicated situation dealing with a non-selfadjoint eigenvalue problem. In this work we employed a variety of variational techniques under various assumptions on the index of refraction as well as the size of the Dirichlet obstacle [15].

6.1.4. *The factorization method for inverse scattering problems*

6.1.4.1. *The factorization method for cracks with impedance boundary conditions*

Participants: Yosra Boukari, Housseem Haddar.

We use the Factorization method to retrieve the shape of cracks with impedance boundary conditions from farfields associated with incident plane waves at a fixed frequency. This work is an extension of the study initiated by Kirsch and Ritter [Inverse Problems, 16, pp. 89-105, 2000] where the case of sound soft cracks is considered. We address here the scalar problem and provide theoretical validation of the method when the impedance boundary conditions hold on both sides of the crack. We then deduce an inversion algorithm and present some validating numerical results in the case of simply and multiply connected cracks [38].

6.1.4.2. *The factorization method for EIT with uncertain background*

Participants: Giovanni Migliorati, Housseem Haddar.

We extended the Factorization Method for Electrical Impedance Tomography to the case of background featuring uncertainty. This work is based on our earlier algorithm for known but inhomogeneous backgrounds. We developed three methodologies to apply the Factorization Method to the more difficult case of piecewise constant but uncertain background. The first one is based on a recovery of the background through an optimization scheme and is well adapted to relatively low dimensional random variables describing the background. The second one is based on a weighted combination of the indicator functions provided by the Factorization Method for different realizations of the random variables describing the uncertain background. We show through numerical experiments that this procedure is well suited to the case where many realizations of the measurement operators are available. The third strategy is a variant of the previous one when measurements for the inclusion-free background are available. In that case, a single pair of measurements is sufficient to achieve comparable accuracy to the deterministic case [42].

6.1.4.3. *The factorization method for GIBC*

Participants: Mathieu Chamaillard, Nicolas Chaulet, Housseem Haddar.

We are concerned with the identification of some obstacle and some Generalized Impedance Boundary Conditions (GIBC) on the boundary of such obstacle from far field measurements generated by the scattering of harmonic incident waves. The GIBCs are approximate models for thin coatings, corrugated surfaces, rough surfaces or imperfectly conducting media.

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

6.2. Iterative Methods for Non-linear Inverse Problems

6.2.1. *Inverse medium problem for axisymmetric eddy current models*

Participants: Housseem Haddar, Zixian Jiang, Kamel Riahi.

We continued our developments of shape optimization methods for inclusion detection in an axisymmetric eddy current model. This problem is motivated by non-destructive testing methodologies for steam generators. We are finalizing our joint work with A. Lechleiter on numerical methods for the solution of the direct problem in weighted Sobolev spaces using appropriate Dirichlet-to-Neumann mappings to bound the computational domain. We are also finalizing jointly with M. El Guedri the work on inverse solver using a regularized steepest descent method for the problem of identifying a magnetite deposits using axial eddy current probe.

We are currently investigating two research directions:

- The development of asymptotic models to identify thin highly conducting deposits. We derived three possible asymptotic models that can be exploited in the inverse problem. The numerical validation is under study.
- The extension of this work to 3D configurations with axisymmetric configuration at infinity, which has been started with the PostDoc of K. Riahi.

6.2.2. *A min-max formulation for inverse scattering problems*

Participants: Grégoire Allaire, Housseem Haddar, Dimitri Nicolas.

After having developed an inverse solver combining the use of Level-Set method and topological gradient method for multistatic inverse scattering problem and numerically showed how convergence can be achieved with initial guess provided by the Linear Sampling Method, we explored the use of an objective function that would lead to quicker and more stable reconstructions. This has been achieved through maximizing the least-square difference with respect to the Herglotz kernel of used incident wave while minimizing with respect to the geometrical parameters. Preliminary numerical experimentations showed that this procedure is viable and lead to quicker inversion algorithms [5].

6.2.3. *The conformal mapping method and inverse scattering at low frequencies*

Participant: Housseem Haddar.

Together with R. Kress we have employed a conformal mapping technique for the inverse problem to reconstruct a perfectly conducting inclusion in a homogeneous background medium from Cauchy data for electrostatic imaging, that is, for solving an inverse boundary value problem for the Laplace equation. In a recent work [41] we proposed an extension of this approach to inverse obstacle scattering for time-harmonic waves, that is, to the solution of an inverse boundary value problem for the Helmholtz equation. The main idea is to use the conformal mapping algorithm in an iterative procedure to obtain Cauchy data for a Laplace problem from the given Cauchy data for the Helmholtz problem. We presented the foundations of the method together with a convergence result and exhibit the feasibility of the method via numerical examples.

6.2.4. *A steepest descent method for inverse electromagnetic scattering problems*

Participants: Housseem Haddar, Nicolas Chaulet.

In a continuation of our earlier work jointly with L. Bourgeois [13], we studied the application of non linear optimization techniques to solve the inverse scattering problems for the 3D Maxwell's equations with generalized impedance boundary conditions. We characterized the shape derivative in the case where the GIBC is defined by a second order surface operator. We then applied a boundary variation method based on a regularized steepest descent to solve the 3-D inverse problem with partial farfield data. The obtained numerical results demonstrated the possibility of identifying the shape of coated objects as well as the parameters of the coating in the 3D Maxwell case.

6.3. Shape and topology optimization

6.3.1. *Geometric constraints in shape and topology optimization*

Participant: Grégoire Allaire.

With François Jouve (LJLL) and Georgios Michailidis (Renault and CMAP), we propose a method to handle geometric constraints in shape and topology optimization. In the framework of the level-set method we rely on a notion of local thickness which is computed using the signed-distance function to the boundary of the shape. We implement this method in two and three space dimensions for a model of linear elasticity. We consider various formulations of the constrained optimization problem and compute a shape derivative to advect the shape. We discuss different ways to handle the constraints. The resulting optimized shape is strongly dependent on the initial guess and on the way the constraints are being treated.

6.3.2. *A hybrid optimization method*

Participant: Grégoire Allaire.

With Charles Dapogny (Renault and LJLL) and Pascal Frey (LJLL) we propose a method for structural optimization that relies on two alternative descriptions of shapes : on the one hand, they are exactly meshed so that mechanical evaluations by finite elements are accurate ; on the other hand, we resort to a level-set characterization to describe their deformation along the shape gradient. The key ingredient is a meshing algorithm for building a mesh, suitable for numerical computations, out of a piecewise linear level-set function on an unstructured mesh. Therefore, our approach is at the same time a geometric optimization method (since shapes are exactly meshed) and a topology optimization method (since the topology of successive shapes can change thanks to the power of the level-set method).

6.3.3. *DeHomogenization*

Participant: Olivier Pantz.

In most shape optimization problems, the optimal solution does not belong to the set of genuine shapes but is a composite structure. The homogenization method consists in relaxing the original problem thereby extending the set of admissible structures to composite shapes. From the numerical viewpoint, an important asset of the homogenization method with respect to traditional geometrical optimization is that the computed optimal shape is quite independent from the initial guess (even if only a partial relaxation is performed). Nevertheless, the optimal shape being a composite, a post-treatment is needed in order to produce an almost optimal non-composite (i.e. workable) shape. The classical approach consists in penalizing the intermediate densities of material, but the obtained result deeply depends on the underlying mesh used and the details level is not controllable. We proposed in [51] a new post-treatment method for the compliance minimization problem of an elastic structure. The main idea is to approximate the optimal composite shape with a locally periodic composite and to build a sequence of genuine shapes converging toward this composite structure. This method allows us to balance the level of details of the final shape and its optimality. Nevertheless, it was restricted to particular optimal shapes, depending on the topological structure of the lattice describing the arrangement of the holes of the composite. We lifted this restriction in order to extend our method to any optimal composite structure for the compliance minimization problem in [50]. Since, the method has been improved and a new article presenting the last results is in preparation. Moreover, we intend to extend this approach to other kinds of cost functions. A first attempt, based on a gradient method, has been made. Unfortunately, it was leading to local minima. Thus a new strategy has to be worked out. It will be mainly based on the same ideas than the one developed for the compliance minimization problem, but some difficulties are still to be overcome.

6.3.4. *Level-Set Method*

Participant: Olivier Pantz.

We have begun to work, with Gabriel Delgado, on a new level-set optimization method, based on a gradient method. The key idea consists in computing directly the derivative of the discretized cost functions. The main advantage is that it is usually more simple to implement than the standard approach (consisting in using a discretized version of the gradient of the cost function). Moreover, the results obtained are as good or even better than the one obtained in previous works. Nevertheless, this method has its drawbacks, since the cost function is only derivable almost everywhere (the zero level-set has to be transverse to the triangulation of the mesh). It follows that convergence toward the minimum by the gradient method is not granted. To overcome this problem, we intend to use a mix-formulation for the state function. Unfortunately, such a formulation, in the case of linear elasticity is quite difficult to obtain. We thus intend to begin with the simplest scalar case, for which a lot more hybrid formulations are available.

6.3.5. *Robust Optimization*

Participant: Olivier Pantz.

One of the main problem in shape optimization problems is due to the fact that the gradient is never computed exactly. When the current solution is far from a local optimum, this is not a problem: even a rough approximation of the gradient enable us to exhibit a descent direction. On the contrary, when close to a local optimal, a very precise computation of the gradient is needed. We intend, with G. Delgado, to use a-posteriori error estimates evaluate the errors made on the computation of the gradient and to ensure that at each step, a genuine descent direction is used in the gradient method.

6.3.6. *Level-set method applied to structural optimization with contact*

Participants: Houssem Haddar, Olivier Pantz.

The current study covers the design and implementation of a method for topological shape optimization in order to optimize multi-connected structures taking into account the contact that may arise between the different components. This project is motivated by the optimization of leaf springs, issue proposed by the company CORTEL and is conducted in the framework of the Master internship of M. Mahjoub. We proposed a method that relies on the use of a Level Set Method coupled with a penalty method to handle contact with different components. The level set function is used for instance to construct the penalization functional. Preliminary results showed that the method efficiently handle optimal design with a targeted non linear deformation behavior prescribed by the manufacturer.

6.3.7. *Optimization of a sodium fast reactor core*

Participants: Grégoire Allaire, Olivier Pantz.

In collaboration with D. Schmidt, G. Allaire and E. Dombre, we apply the geometrical shape optimization method for the design of a SFR (Sodium Fast reactor) core in order to minimize a thermal counter-reaction known as the sodium void effect. In this kind of reactor, by increasing the temperature, the core may become liable to a strong increase of reactivity ρ , a key-parameter governing the chain-reaction at quasi-static states. We first use the 1 group energy diffusion model and give the generalization to the 2 groups energy equation. We then give some numerical results in the case of the 1 group energy equation. Note that the application of our method leads to some designs whose interfaces can be parametrized by very smooth curves which can stand very far from realistic designs. We don't explain here the method that it would be possible to use for recovering an operational design but there exists several penalization methods that could be employed to this end. This work was partially sponsored by EDF. Our results will be published in the proceedings of the CEMRACS'11, during which part of the results have been obtained.

6.4. Asymptotic Analysis

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

Participants: Nicolas Chaulet, Houssein Haddar.

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

6.4.2. *Effective boundary conditions for thin periodic coatings*

Participants: Mathieu Chamaillard, Houssein Haddar.

This topic is the object of a collaboration with Patrick Joly and is a continuation of our earlier work on interface conditions done in the framework of the PhD thesis of Berangère Delourme [18], [17]. The goal here is to derive effective conditions that model scattering from thin periodic coatings where the thickness and the periodicity are of the same length but very small compared to the wavelength. The originality of our work, compared to abundant literature is to consider the case of arbitrary geometry (2-D or 3-D) and to consider higher order approximate models. We formally derived third order effective conditions after exhibiting the full asymptotic expansion of the solution in terms of the periodicity length.

6.4.3. *Homogenization of thermal radiative transfer models in heterogeneous domains*

Participant: Grégoire Allaire.

With my former PhD student, Zakaria Habibi, we studied the homogenization of heat transfer in periodic porous media where the fluid part is made of long thin parallel cylinders, the diameter of which is of the same order than the period. The heat is transported by conduction in the solid part of the domain and by conduction, convection and radiative transfer in the fluid part (the cylinders). A non-local boundary condition models the radiative heat transfer on the cylinder walls. To obtain the homogenized problem we first use a formal two-scale asymptotic expansion method. The resulting effective model is a convection-diffusion equation posed in a homogeneous domain with homogenized coefficients evaluated by solving so-called cell problems where radiative transfer is taken into account. In a second step we rigorously justify the homogenization process by using the notion of two-scale convergence. One feature of this work is that it combines homogenization with a 3D to 2D asymptotic analysis since the radiative transfer in the limit cell problem is purely two-dimensional. Eventually, we provide some 3D numerical results in order to show the convergence and the computational advantages of our homogenization method. We also focused on the contribution of the so-called second order corrector. If the source term is a periodically oscillating function (which is the case in our application to nuclear reactor physics), a strong gradient of the temperature takes place in each periodicity cell, corresponding to a large heat flux between the sources and the perforations. This effect cannot be taken into account by the homogenized model, neither by the first order corrector. We show that this local gradient effect can be reproduced if the second order corrector is added to the reconstructed solution. Z. Habibi received the 2012 Paul Caseau PhD prize in the field "modélisation et simulation numérique", prize created by the Académie des technologies and EDF.

6.4.4. Homogenization of complex flows in porous media

Participant: Grégoire Allaire.

With Robert Brizzi (CMAP), Jean-François Dufrêche (Marcoule and Montpellier), Andro Mikelic (Lyon 1) and Andrey Piatnitski (Narvik) we studied the homogenization (or upscaling) of a system of partial differential equations describing the non-ideal transport of a N-component electrolyte in a dilute Newtonian solvent through a rigid porous medium. Non-ideal effects are taken into account by the mean spherical approximation (MSA) model. We first study the existence of equilibrium solutions in the absence of external forces. When the motion is governed by a small static electric field and a small hydrodynamic force, we generalize O'Brien's argument to deduce a linearized model. We then proceed to the homogenization of these linearized equations and prove that the effective tensor satisfies Onsager properties, namely is symmetric positive definite. We eventually make numerical comparisons with the ideal case.

With my PhD student Harsha Hutridurga we study the convection and diffusion of a solute in a porous medium in the presence of a linear chemical reaction of adsorption/desorption on the pore surfaces. The mathematical model is a system of two coupled convection-diffusion equations, one in the bulk of the saturated fluid flowing in the porous medium, the other on the pore surface, at the interface with the solid part of the porous medium. The coupling takes place through a linear reaction term expressing the exchange of mass between the bulk concentration and the surface concentration. By a method of two-scale asymptotic expansion with drift we obtain the homogenized problem in a moving frame. We rigorously justify our upscaling approach by using the notion of two-scale convergence with drift. Some 2-d numerical tests are performed in order to study the effect of variations of the adsorption rate constant and surface molecular diffusion on the effective dispersion tensor.

With Irina Pankratova (Narvik) and Andrey Piatnitski (Narvik) we consider the homogenization of a non-stationary convection-diffusion equation posed in a bounded domain with periodically oscillating coefficients and homogeneous Dirichlet boundary conditions. Assuming that the convection term is large, we give the asymptotic profile of the solution and determine its rate of decay. In particular, it allows us to characterize the "hot spot", i.e., the precise asymptotic location of the solution maximum which lies close to the domain boundary and is also the point of concentration. Due to the competition between convection and diffusion, the position of the "hot spot" is not always intuitive as exemplified in some numerical tests.

6.4.5. Multiscale finite elements

Participant: Grégoire Allaire.

With my PhD student Franck Ouaki we introduced a new multiscale finite element method to solve convection-diffusion problems where both velocity and diffusion coefficient exhibit strong variations at a much smaller scale than the domain of resolution. In that case, classical discretization methods, used at the scale of the heterogeneities, turn out to be too costly or useless. Our method aims at solving this kind of problems on coarser grids with respect to the size of the heterogeneities by means of particular basis functions. These basis functions are solutions to cell problems and are designed to reproduce the variations of the solution on an underlying fine grid. Since all cell problems are independent from each other, these problems can be solved in parallel, which makes the method very efficient when used on parallel architectures. The convergence proof of our method is still in progress. But, on the basis of results of periodic homogenization, an a priori error estimate, that represents a first step in the proof, has already been proved. A 2-d numerical implementation in FreeFem++ has also been performed.

6.4.6. *A new shell modeling modeling*

Participant: Olivier Pantz.

Using a formal asymptotic expansion, we have proved with K. Trabelsi, that non-isotropic thin-structure could behave (when the thickness is small) like a shell combining both membrane and bending effects. It is the first time to our knowledge that such a model is derived. An article on this is currently under review.

6.4.7. *A new Liouville type Rigidity Theorem*

Participant: Olivier Pantz.

We have recently developed a new Liouville type Rigidity Theorem. Considering a cylindrical shaped solid, we prove that if the local area of the cross sections is preserved together with the length of the fibers, then the deformation is a combination of a planar deformation and a rigid motion. The results currently obtained are limited to regular deformations and we are currently working with B. Merlet to extend them. Nevertheless, we mainly focus on the case where the conditions imposed to the local area of the cross sections and the length of the fibers are only "almost" fulfilled. This will enable us to derive rigorously new non linear shell models combining both membrane and flexural effects that we have obtained using a formal approach. An article on this subject is currently in preparation.

6.4.8. *Lattices*

Participant: Olivier Pantz.

With A. Raoult and N. Meunier (Université Paris Descartes), we have compute the asymptotic limit of a square lattice with three-points interactions. Considering such interaction is important in the case of square lattices, because such lattices, if only endowed with two-points closest neighbor interactions, show no resistance to compression, what is quit restrictive. We prove in particular that under some symmetry assumptions on the type of elementary interactions, no micro-relaxation do occur and that the limit can be obtained by a mere quasiconvexication. Without those assumptions, the computation of the limit requires the resolution of a homogenization problem on an infinite number of cells, what is usually out of reach. Our work has been published in M3AS [26].

6.5. Diffusion MRI

Participants: Jing-Rebecca Li, Housseem Haddar, Julien Coatléven, Dang Van Nguyen, Hang Tuan Nguyen.

Diffusion Magnetic Resonance Imaging (DMRI) is a promising tool to obtain useful information on microscopic structure and has been extensively applied to biological tissues. In particular, we would like to focus on two applications:

- inferring from DMRI measurements changes in the cellular volume fraction occurring upon various physiological or pathological conditions.

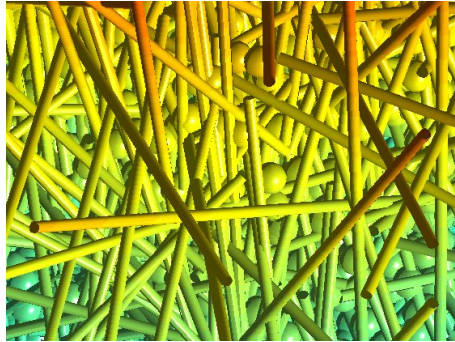


Figure 1. Computational domain for simulating diffusion in cerebral gray matter.

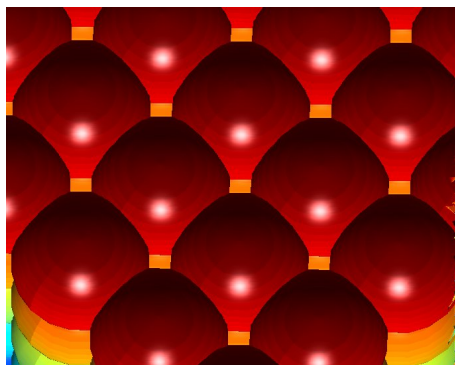


Figure 2. Computational domain for simulating tumor cells.

This application is one of the first to show the promise of DMRI because it can detect acute cerebral ischemia (cell swelling) on the basis of lower than normal apparent diffusion coefficient a few minutes after stroke.

- estimating the average cell size in the case of tumor imaging

This application is useful as a diagnostic tool as well as a tool for the evaluation of tumor treatments.

For both of the above applications we approach the problem via the following steps:

- Construct reduced models of the multiple-compartment Bloch-Torrey partial differential equation (PDE) using homogenization methods.
- Invert the resulting reduced models for the biological parameters of interest: the cellular volume fraction in the first case, and the average distance between neighboring cells in the second case.

We obtained the following results.

- We generated fairly complicated meshes that can be used to simulate diffusion in cerebral gray matter. In the Finite Elements code, this required using the mesh generation software Salome, developed at the CEA Saclay. We are working on the problem of increasing the cellular volume fraction to a physically realistic level, which is difficult for the mesh generator because of the very small distances between the neurons.
- We developed a homogenized model for the apparent diffusion coefficient (the slope of the log of the DMRI signal) of heterogenous cellular domains. An article on this topic has been submitted.
- We developed a reduce model of the complete DMRI signal (not just the slope as in the above) using more sophisticated homogenization methods. An article on this topic is under preparation.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Gregoire Allaire is in charge of the RODIN project. This is a consortium of various companies and universities which has been sponsored by the FUI AAP 13 for 3 years, starting on July 2012. The industrial partners are: Renault, EADS, ESI, Eurodecision, Alneos, DPS. The academic partners are: CMAP at Ecole Polytechnique, Laboratoire J.-L. Lions at Paris 6 and 7 Universities, centre de recherches Bordeaux Su-Ouest at Inria. The goal of the RODIN project is to perform research and develop a computer code on geometry and topology optimization of solid structures, based on the level set method. RODIN is the acronym of "Robust structural Optimization for Design in Industry".
- Grègoire Allaire has a contract with IFPEN on multiscale finite elements for two-phase flows in porous media (in the framework of the PhD thesis of F. Ouaki, to be defended in 2013).
- Grègoire Allaire has a contract with EADS/IW on topology optimization for composite panels drapping (in the framework of the PhD thesis of G. Delgado, to be defended in 2013).
- Grègoire Allaire has a contract with Renault on geometry and topology optimization of structures (in the framework of the two PhD theses of Ch. Dapogny, with the co-advising of P. Frey, to be defended in 2013, and G. Michailidis, with the co-advising of F. Jouve, to be defended in 2013).
- Houssein Haddar is in charge of DEFI part of the FUI project Nanolytix. This three years project started in October 2012 and involves Xenocs (coordinator), imXPAD, Arkema, Inria (DEFI) and CEA-Leti. It aims at building a compact and easy-to use device that images nonaparticles using X-ray diffraction at small or wide angles (SAXS and WAXS technologies). We are in charge of direct and inverse simulation of the SAXS and WAXS experiments.
- Houssein Haddar is in charge of the electromagnetic simulation work package of the FUI project Tandem. This three years project started in December 2012 and 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.

- Housseem Haddar has a contract with EDF R&D on non destructive testing of concrete materials (in the framework of the PhD thesis of Lorenzo Audibert, to be defended in 2015)
- Housseem Haddar has a contract with EDF R&D on data assimilation for temperature estimates in nuclear reactors (in the framework of the PhD thesis of Thibault Mercier, to be defended in 2015)
- Housseem Haddar is coordinating the contract EDF R&D on non eddy current non destructive testing. This contract involves Zixian Jiang (PhD to be defended in 2013) and a two years PostDoc, Kamel Riahi.

7.2. Bilateral Grants with Industry

- Grègoire Allaire is a scientific adviser at the DM2S department of CEA Saclay.

8. Partnerships and Cooperations

8.1. Regional Initiatives

- Olivier Pantz is in charge of the Gaspard Monge Program for Optimization and operations research (PGMO) *Optimization of a Fast Sodium Reactor*

8.2. National Initiatives

8.2.1. ANR

- J.R. Li is the coordinator of the project Simulation du signal d'IRM diffusion dans des tissus biologiques (SIMUDMRI), funded 2010-2013 by the ANR Program COSINUS. Participants : Jing-Rebecca Li, Housseem Haddar, Dang Van Nguyen. Joint proposal between Inria-Saclay and CEA Neurospin. <http://www.cmap.polytechnique.fr/~jingrebeccali/grants/simudmri.html>
- H. Haddar is the DEFI coordinator of the ANR: Modelization and numerical simulation of wave propagation in metamaterials (METAMATH), program MN, 2011-2015. This is a joint ANR with POEMS, Inria Saclay Ile de France project team (Coordinator, S. Fliss), DMIA, Département de Mathématiques de l'ISAE and IMATH, Laboratoire de Mathématiques de l'Université de Toulon. <https://www.rocq.inria.fr/poems/metamath>

8.3. European Initiatives

8.3.1. Collaborations with Major European Organizations

Partner 1: University of Goettingen, Department of Math. (Germany)

Development of conformal mapping method to electrostatic inverse problems. Correspondant: Rainer Kress.

Partner 2: University of Genova, Department of Math. (Italy)

Development of qualitative methods in inverse scattering problems. Correspondant: Michele Piana.

8.4. International Initiatives

8.4.1. Inria Associate Teams

8.4.1.1. ISIP

Title: Inverse Scattering and Identification Problems

Inria principal investigator: Housseem HADDAR

International Partner (Institution - Laboratory - Researcher):

University of Delaware (United States) - Mathematical Department - Fioralba Cakoni

Duration: 2008 - 2013

See also: <http://www.cmap.polytechnique.fr/~defi/ISIP/isip.html>

The associated team concentrates on the use of qualitative methods in electromagnetic inverse scattering theory with applications to the imaging of urban infrastructure, the nondestructive evaluation of coated materials and medical imaging. Most of the effort is focused in the solution of the inverse problems using time harmonic waves, in particular for frequencies in the resonance regime.

8.4.2. Inria International Partners

- Close collaboration with the former member of our EPI, A. Lechleiter, who is now professor at University of Bremen. Joint PhD advising of T. Rienmuller, partly funded by French-German university.

8.4.3. Participation In International Programs

- H. Haddar is member of the EPIC, an Inria team in the framework of LIRIMA.
- Olivier Pantz is in charge of the french side of the PHC (Hubert Curien Project) *Sur l'étude de quelques problèmes d'équations aux dérivées partielles issus de la physique* (with H. Zorgati of the University of Tunis in charge for the Tunisian side).

8.5. International Research Visitors

8.5.1. Visits of International Scientists

8.5.1.1. Internships

Mohamed MAHJOUB (from Feb 2012 until Aug 2012)

Subject: Level set method applied to structural optimization with contact

Institution: Ecole Polytechnique de Tunisie (Tunisia)

Jackie FAN YAN (from June 2012 until Aug 2012)

Subject: Direct and inverse simulation of hyper lenses

Institution: University of Delaware (Tunisia)

9. Dissemination

9.1. Scientific Animation

- Grègoire Allaire is the President of SMAI (Société de Mathématiques Appliquées et Industrielles).
- Grègoire Allaire is a board member of Institut Henri Poincaré (IHP).
- Grègoire Allaire is the chairman of the Gaspard Monge Program in Optimization (PGMO) at the Jacques Hadamard Mathematical Foundation.
- Grègoire Allaire is a member of the following editorial boards: book series "Mathématiques et Applications" of SMAI and Springer, ESAIM/COCV, Structural and Multidisciplinary Optimization, Discrete and Continuous Dynamical Systems Series, Computational and Applied Mathematics, Mathematical Models and Methods in Applied Sciences (M3AS), Annali dell'Università di Ferrara.
- Houssein Haddar is a guest editor (jointly with Fioralba Cakoni) of a special issue of Inverse problems on transmission eigenvalues.
- Jing-Rebecca Li is an Associate Editor of the SIAM Journal on Scientific Computing.

9.1.1. Conference organization

- G. Allaire (Chair), H. Haddar and O. Pantz are co-organizers of PICO6 6th edition (Inverse Problems, Control and Shape Optimization), April 2-4 2012.

- H. Haddar is the organizer of the minisymposium "Inverse Problems and Applications" at CANUM, 2012, 21 mai - 25 mai 2012, Superbesse.
- J.-R. Li is a co-organizer of the mini-symposium "Simulation and modeling applied to diffusion magnetic resonance imaging" at the SIAM Computational Science and Engineering Conference Feb 2013.

9.1.2. Conference attendance

- Nicolas Chaulet, "Reconstruction of a perfectly conducting obstacle coated with a thin dielectric layer", PICO'F 12, Palaiseau (France), 4-6/04/2012
- Nicolas Chaulet, "A factorization method for support characterization of an obstacle with a generalized impedance boundary condition", IPMS conference, Antalya (Turkey), 21-26/05/2012
- Olivier Pantz, "The dehomogenization method", Seminar University of Sciences of Tunis (November 2012)
- Olivier Pantz, Participation to the kickoff workshop of the ANR "Geometria", Lyon (October 2012)
- Olivier Pantz, "Numerical Simulation of the Dynamic of Red Blood Cells" Colloquium MAP5, University Paris-Descartes (February 2012)
- Grégoire Allaire, 83rd Annual Meeting of GAMM, Darmstadt (march 2012).
- Grégoire Allaire, Conference Dynacomp, Arcachon (may 2012).
- Grégoire Allaire, Workshop "Exotic Structures and Homogenization", APM12, Saint Petersburg (july 2012).
- Grégoire Allaire, Conference "variational models and methods for evolution", Levico (september 2012).
- Houssein Haddar, Canum, 2012, 21 mai - 25 mai 2012, Superbesse
- Houssein Haddar, Congrès de Méthodes numériques et Modélisation ENIT-LAMSIN, Tunis, 13-15 December 2012.
- Dinh Liem Nguyen, International Conference on Inverse Problems and Related Topics 2012, October 21-26, 2012, Southeast University, Nanjing, China.
- Dinh Liem Nguyen, Conference Inverse Days 2012, December 17-20, 2012, University of Jyväskylä, Jyväskylä, Finland.
- Zixian Jiang, Poster at the conference on Inverse Problems, Control and Shape Optimization (PICO'F 2012), Ecole Polytechnique, Palaiseau, France, April 2012.
- Zixian Jiang, Talk in the minisymposium *Inverse Problems in Biomedical engineering* at the International Conference on Inverse Problems and Related Topics (ICIP 2012), Southeast University, Nanjing, China, October 2012.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: Nicolas Chaulet, *Equations différentielles et introduction à l'automatique*, ENSTA, Paris (1st year).

Licence: Nicolas Chaulet, *La méthode des éléments finis*, ENSTA, Paris (2nd year).

Licence: O. Pantz, Tutorial Classes in "Numerical analysis et Optimization", 64h, L3, École Polytechnique.

Licence: H. Haddar, Tutorial Classes in "Numerical analysis et Optimization", 64h, L3, École Polytechnique.

Licence: Grégoire Allaire teaches a semester course on numerical analysis and optimization in the second year (senior undergraduate level). See the web page: http://www.cmap.polytechnique.fr/~allaire/cours_X_annee2.html

Master: O. Pantz, Tutorial Classes in "Structural Optimization" (G. Allaire) 14h, M1, École Polytechnique.

Master: O. Pantz, "Troisième Ateliers de Simulation Numérique" , 24h TD, M1, Univeristy of Ouragla, Algeria, December 2012.

Master: O. Pantz, Tutorial Classes and Courses in FreeFem++, 24h, M1, University Badji Mokhtar Annaba, Algeria, April 2012.

Master: O. Pantz, Project training in Numerical Analysis (1 project - "Shape optimization by the Level-Set Method in 3d"), M1, Ecole Polytechnique.

Master: Grègoire Allaire teaches a course on optimal design of structures in the third year (first year of a Master program). See the web page: http://www.cmap.polytechnique.fr/~allaire/cours_X_majeure.html

Master: Grègoire Allaire teaches together with François Golse a course on transport and diffusion in the third year (first year of a Master program). See the web page: http://www.cmap.polytechnique.fr/~allaire/cours_map567.html

Master: Grègoire Allaire teaches together with François Alouges a course on homogenization in the fourth year (second year of a Master program). See the web page: <http://www.cmap.polytechnique.fr/~allaire/homogenization.html>

Master: Housseem Haddar teaches together with Antonin Chambolle a course on Mathematics of Inverse Problems (M2, AN&EDP, Paris 6 and Eole Polytechnique).

9.2.2. Supervision

PhD in progress: L. Azem, Fracture and damage: Modeling and Simulation, Olivier Pantz (with Zorgati).

PhD in progress : H. T. Nguyen, Simplified models and inverse problems for diffusion MRI, 2011, Jing-rebecca Li (with Denis Grebenkov and Cyril Poupon).

PhD in progress : D. V. Nguyen, Efficient finite-element method to solve PDE problems in diffusion MRI, 2011, Jing-Rebecca Li (with Denis Grebenkov).

PhD in progress : F. Ouaki, On multi-scale numerical methods for multiphasic transport in porous media, 2010, Grègoire Allaire.

PhD in progress : G. Delgado, Optimal design of the draping of composite materials, 2010, Grègoire Allaire.

PhD in progress : G. Michailidis, On topology optimization with feasibility constraints, 2010, Grègoire Allaire (with F. Jouve)

PhD in progress : Z. Jiang, Eddy current probing of axisymmetric tubes, 2010, Housseem Haddar.

PhD in progress : G. Migliorati, Electrostatic Imaging with uncertain backgrounds, 2010, Housseem Haddar (with F. Nobile)

PhD in progress : L. Audibert, Non-destructive testing of concrete like materials, 2012, Housseem Haddar.

PhD in progress : T. Mercier, data assimilation for temprature estimates of nuclear fuel powerplant, 2012, Housseem Haddar.

PhD in progress: M. Chamaillard, Effective boundary conditions for thin periodic coatings, Ecole Polytechnique, 2011, Housseem Haddar (with P. Joly).

Master: O.Pantz, Internship co-supervisor with G. Allaire and D. Shmitt (EDF) of G. Gourlaouen (INSTN, École des Mines de Nancy) on "The Shape Optimization of a Sodium Fast Reactor Core", M2.

PhD: Y. Boukari, Méthodes innovantes en contrôle non destructif des structures: applications à la détection de fissures, Ecole Polytechnique and ENIT, January 2012, H. Haddar and F. Ben Hassen.

PhD: G. Giorgi, Mathematical tools for microwave mammography and prostate cryosurgery, University of Genova, April 2012, H. Haddar and M. Piana.

PhD: D. Nicolas, Couplage de méthodes d'échantillonnage et de méthodes d'optimisation de forme pour des problèmes de diffraction inverse, Ecole Polytechnique, November 2012, G. Allaire and H. Haddar.

PhD: N. Chaulet, Modèles d'impédance généralisée en diffraction inverse, Ecole Polytechnique, November 2012, L. Bourgeois and H. Haddar.

PhD: D.L. Nguyen, Spectral Methods for Direct and Inverse Scattering from Periodic Structures, Ecole Polytechnique, December 2012, H. Haddar and A. Lechleiter.

HdR: O. Pantz, Quelques problèmes variationnels: Optimisation de forme, contacts et analyse asymptotique, Université Paris Sud, December 2012.

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Publications of the year

Doctoral Dissertations and Habilitation Theses

- [1] Y. BOUKARI. *Méthodes innovantes en contrôle non destructif des structures: applications à la détection de fissures*, Ecole Polytechnique X, January 2012, <http://hal.inria.fr/pastel-00702479>.
- [2] N. CHAULET. *Modèles d'impédance généralisée en diffraction inverse*, Ecole Polytechnique X, November 2012, <http://hal.inria.fr/pastel-00761642>.
- [3] G. GIORGI. *Mathematical tools for microwave mammography and prostate cryosurgery*, University of Genova, April 2012.
- [4] D. L. NGUYEN. *Spectral Methods for Direct and Inverse Scattering from Periodic Structures*, Ecole Polytechnique X, December 2012.
- [5] D. NICOLAS. *Couplage de méthodes d'échantillonnage et de méthodes d'optimisation de forme pour des problèmes de diffraction inverse*, Ecole Polytechnique X, November 2012.
- [6] O. PANTZ. *Quelques problèmes variationnels: Optimisation de forme, contacts et analyse asymptotique*, Université Paris-Sud, 2012, Habilitation à Diriger des Recherches.

Articles in International Peer-Reviewed Journals

- [7] G. ALLAIRE, Y. CAPDEBOSQ, M. PUEL. *Homogenization of a One-Dimensional Spectral Problem for a Singularly Perturbed Elliptic Operator with Neumann Boundary Conditions*, in "DCDS-B", 2012.
- [8] G. ALLAIRE, Z. HABIBI. *Second order corrector in the homogenization of a conductive-radiative heat transfer problem*, in "DCDS-B", 2012.
- [9] G. ALLAIRE, H. HUTRIDURGA. *Homogenization of reactive flows in porous media and competition between bulk and surface diffusion*, in "IMA J. Appl. Math", 2012.

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- [10] G. ALLAIRE, I. PANKRATOVA, A. PIATNITSKI. *Homogenization and concentration for a diffusion equation with large convection in a bounded domain*, in "Journal of Functional Analysis", 2012.
- [11] G. ALLAIRE, I. PANKRATOVA, A. PIATNITSKI. *Homogenization of a nonstationary convection-diffusion equation in a thin rod and in a layer*, in "SeMA Journal", 2012.
- [12] F. BEN HASSEN, Y. BOUKARI, H. HADDAR. *Application of the linear sampling method to identify cracks with impedance boundary conditions*, in "Inverse Problems in Science and Engineering", 2012, p. 1-25 [DOI : 10.1080/17415977.2012.686997], <http://hal.inria.fr/hal-00743816>.
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- [19] E. DOMBRE, G. ALLAIRE, O. PANTZ. *Shape Optimization of a Sodium Fast Reactor Core*, in "ESAIM Proceedings", December 2012, vol. 38, p. 319 - 334, CEMRACS'11: Multiscale Coupling of Complex Models in Scientific Computing.
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- [27] G. ALLAIRE, S. DESROZIERS, G. ENCHARY, F. OUAKI. *A multiscale finite element method for transport modeling*, in "CD-ROM Proceedings of the 6th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2012)", Vienna University of Technology, Austria, 2012.

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- [28] J.-R. LI, D. GREBENKOV, C. POUPON, D. LE BIHAN. *An approximate analytical formula for the long time apparent diffusion coefficient*, in "ISMRM 2012", Melbourne, Australie, May 2012.
- [29] D. V. NGUYEN, D. GREBENKOV, C. POUPON, D. LE BIHAN, J.-R. LI. *Effective diffusion tensor computed by homogenization*, in "MRPM11 - The 11th International Bologna Conference on Magnetic Resonance in Porous Media", University of Surrey, Guildford, UK, 2012, <http://hal.inria.fr/hal-00764337>.
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Scientific Books (or Scientific Book chapters)

- [32] F. CAKONI, H. HADDAR. *Transmission Eigenvalues in Inverse Scattering Theory*, in "Inside Out II", G. UHLMANN (editor), MSRI Publications, 2012, vol. 60, p. 527-578, <http://hal.inria.fr/hal-00741615>.

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- [33] E. DOMBRE, G. ALLAIRE, O. PANTZ. *Shape Optimization of a Sodium Fast Reactor Core*, CMAP, 2012, n^o R.I. 750.
- [34] H. HADDAR, A. LECHLEITER, S. MARMORAT. *An improved time domain linear sampling method for Robin and Neumann obstacles*, Inria, October 2012, n^o RR-7835, 32, <http://hal.inria.fr/hal-00651301>.

Other Publications

- [35] G. ALLAIRE, R. BRIZZI, J.-F. DUFRÊCHE, A. MIKELIC, A. PIATNITSKI. *Ion transport in porous media: derivation of the macroscopic equations using upscaling and properties of the effective coefficients*, 2012, Submitted.
- [36] G. ALLAIRE, Z. HABIBI. *Homogenization of a Conductive, Convective and Radiative Heat Transfer Problem in a Heterogeneous Domain*, 2012, Submitted.
- [37] G. ALLAIRE, M. PALOMBARO, J. RAUCH. *Diffraction of Bloch Wave Packets for Maxwell's Equations*, 2012, Submitted.
- [38] Y. BOUKARI, H. HADDAR. *The Factorization method applied to cracks with impedance boundary conditions*, 2012, Submitted, <http://hal.inria.fr/hal-00768729>.
- [39] J. COATLÉVEN, H. HADDAR, J.-R. LI. *A new macroscopic model including membrane exchange for diffusion MRI*, 2012, Submitted, <http://hal.inria.fr/hal-00768732>.
- [40] D. GREBENKOV, H. T. NGUYEN, J.-R. LI. *A fast random walk algorithm for computing diffusion-weighted NMR signals in multiscale porous media: a feasibility study for a Menger sponge*, 2012, Submitted, <http://hal.inria.fr/hal-00764179>.
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