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ACTIVITY REPORT

Project-Team

SPHINX

Heterogeneous Systems: Inverse Problems, Control and Stabilization, Simulation

IN COLLABORATION WITH: Institut Elie Cartan de Lorraine (IECL)

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Optimization and control of dynamic systems

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Project-Team SPHINX

Creation of the Team: 2015 January 01, updated into Project-Team: 2016 May 01

Keywords

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2 Overall objectives

In this project, we investigate theoretical and numerical mathematical issues concerning heterogeneous physical systems. The heterogeneities we consider result from the fact that the studied systems involve subsystems of different physical nature. In this wide class of problems, we study two types of systems: **fluid-structure interaction systems (FSIS)** and **complex wave systems (CWS)**. In both situations, one has to develop specific methods to take the coupling between the subsystems into account.

(FSIS) Fluid-structure interaction systems appear in many applications: medicine (motion of the blood in veins and arteries), biology (animal locomotion in a fluid, such as swimming fishes or flapping birds but also locomotion of microorganisms, such as amoebas), civil engineering (design of bridges or any structure exposed to the wind or the flow of a river), naval architecture (design of boats and submarines, researching into new propulsion systems for underwater vehicles by imitating the locomotion of aquatic animals). FSIS can be studied by modeling their motions through Partial Differential Equations (PDE) and/or Ordinary Differential Equations (ODE), as is classical in fluid mechanics or in solid mechanics. This leads to the study of difficult nonlinear free boundary problems which have constituted a rich and active domain of research over the last decades.

(CWS) Complex wave systems are involved in a large number of applications in several areas of science and engineering: medicine (breast cancer detection, kidney stone destruction, osteoporosis diagnosis, etc.), telecommunications (in urban or submarine environments, optical fibers, etc.), aeronautics (target detection, aircraft noise reduction, etc.) and, in the longer term, quantum supercomputers. **For direct problems**, most theoretical issues are now widely understood. However, substantial efforts remain to be undertaken concerning the simulation of wave propagation in complex media. Such situations include heterogeneous media with strong local variations of the physical properties (high frequency scattering, multiple scattering media) or quantum fluids (Bose-Einstein condensates). In the first case for instance, the numerical simulation of such direct problems is a hard task, as it generally requires solving ill-conditioned possibly indefinite large size problems, following from space or space-time discretizations of linear or nonlinear evolution PDE set on unbounded domains. **For inverse problems**, many questions are open at both the theoretical (identifiability, stability and robustness, etc.) and practical (reconstruction methods, approximation and convergence analysis, numerical algorithms, etc.) levels.

3 Research program

3.1 Control and stabilization of heterogeneous systems

Fluid-Structure Interaction Systems (FSIS) are present in many physical problems and applications. Their study involves solving several challenging mathematical problems:

- **Nonlinearity:** One has to deal with a system of nonlinear PDE such as the Navier-Stokes or the Euler systems;
- **Coupling:** The corresponding equations couple two systems of different types and the methods associated with each system need to be suitably combined to solve successfully the full problem;
- **Coordinates:** The equations for the structure are classically written with Lagrangian coordinates whereas the equations for the fluid are written with Eulerian coordinates;
- **Free boundary:** The fluid domain is moving and its motion depends on the motion of the structure. The fluid domain is thus an unknown of the problem and one has to solve a free boundary problem.

In order to control such FSIS, one has first to analyze the corresponding system of PDE. The oldest works on FSIS go back to the pioneering contributions of Thomson, Tait and Kirchhoff in the 19th century and Lamb in the 20th century, who considered simplified models (potential fluid or Stokes system). The first mathematical studies in the case of a viscous incompressible fluid modeled by the Navier-Stokes system and a rigid body whose dynamics is modeled by Newton's laws appeared much later [121, 116, 95], and almost all mathematical results on such FSIS have been obtained in the last twenty years.

The most studied FSIS is the problem modeling a **rigid body moving in a viscous incompressible fluid** ([77, 74, 114, 84, 89, 118, 120, 104, 87]). Many other FSIS have been studied as well. Let us mention [106, 92, 88, 78, 65, 83, 64, 85] for different fluids. The case of **deformable structures** has also been considered, either for a fluid inside a moving structure (e.g. blood motion in arteries) or for a moving deformable structure immersed in a fluid (e.g. fish locomotion). The obtained coupled FSIS is a complex system and its study raises several difficulties. The main one comes from the fact that we gather two systems of different nature. Some studies have been performed for approximations of this system: [70, 65, 98, 79, 67]). Without approximations, the only known results [75, 76] were obtained with very strong assumptions on the regularity of the initial data. Such assumptions are not satisfactory but seem inherent to this coupling between two systems of different natures. In order to study self-propelled motions of structures in a fluid, like fish locomotion, one can assume that the **deformation of the structure is prescribed and known**, whereas its displacement remains unknown ([111]). This permits to start the mathematical study of a challenging problem: understanding the locomotion mechanism of aquatic animals. This is related to control or stabilization problems for FSIS. Some first results in this direction were obtained in [93, 66, 108].

3.2 Inverse problems for heterogeneous systems

The area of inverse problems covers a large class of theoretical and practical issues which are important in many applications (see for instance the books of Isakov [94] or Kaltenbacher, Neubauer, and Scherzer [96]). Roughly speaking, an inverse problem is a problem where one attempts to recover an unknown property of a given system from its response to an external probing signal. For systems described by evolution PDE, one can be interested in the reconstruction from partial measurements of the state (initial, final or current), the inputs (a source term, for instance) or the parameters of the model (a physical coefficient for example). For stationary or periodic problems (i.e. problems where the time dependency is given), one can be interested in determining from boundary data a local heterogeneity (shape of an obstacle, value of a physical coefficient describing the medium, etc.). Such inverse problems are known to be generally ill-posed and their study raises the following questions:

- *Uniqueness.* The question here is to know whether the measurements uniquely determine the unknown quantity to be recovered. This theoretical issue is a preliminary step in the study of any inverse problem and can be a hard task.
- *Stability.* When uniqueness is ensured, the question of stability, which is closely related to sensitivity, deserves special attention. Stability estimates provide an upper bound for the parameter error given some uncertainty on the data. This issue is closely related to the so-called observability inequality in systems theory.
- *Reconstruction.* Inverse problems being usually ill-posed, one needs to develop specific reconstruction algorithms which are robust to noise, disturbances and discretization. A wide class of methods is based on optimization techniques.

We can split our research in inverse problems into two classes which both appear in FSIS and CWS:

1. **Identification for evolution PDE.**

   Driven by applications, the identification problem for systems of infinite dimension described by evolution PDE has seen in the last three decades a fast and significant growth. The unknown to be recovered can be the (initial/final) state (e.g. state estimation problems [59, 86, 90, 117] for the design of feedback controllers), an input (for instance source inverse problems [56, 68, 80]) or a parameter of the system. These problems are generally ill-posed and many regularization approaches have been developed. Among the different methods used for identification, let us mention optimization techniques ([73]), specific one-dimensional techniques (like in [60]) or observer-based methods as in [101].

   In the last few years, we have developed observers to solve initial data inverse problems for a class of linear systems of infinite dimension. Let us recall that observers, or Luenberger observers [100], have been introduced in automatic control theory to estimate the state of a dynamical system of finite dimension from the knowledge of an output (for more references, see for instance [105] or [119]). Using observers, we have proposed in [107, 91] an iterative algorithm to reconstruct initial data from partial measurements for some evolution equations. We are deepening our activities in this direction by considering more general operators or more general sources and the reconstruction of coefficients for the wave equation. In connection with this problem, we study the stability in the determination of these coefficients. To achieve this, we use geometrical optics, which is a classical albeit powerful tool to obtain quantitative stability estimates on some inverse problems with a geometrical background, see for instance [62, 61].

2. **Geometric inverse problems.**

We investigate some geometric inverse problems that appear naturally in many applications, like medical imaging and non destructive testing. A typical problem we have in mind is the following: given a domain Ω containing an (unknown) local heterogeneity ω, we consider the boundary value problem of the form

$$\begin{cases} Lu = 0, & (\Omega \setminus \omega) \\ u = f, & (\partial\Omega) \\ Bu = 0, & (\partial\omega) \end{cases}$$

where L is a given partial differential operator describing the physical phenomenon under consideration (typically a second order differential operator), B the (possibly unknown) operator describing the boundary condition on the boundary of the heterogeneity and f the exterior source used to probe the medium. The question is then to recover the shape of ω and/or the boundary operator B from some measurement Mu on the outer boundary $\partial\Omega$. This setting includes in particular inverse scattering problems in acoustics and electromagnetics (in this case Ω is the whole space and the data are far field measurements) and the inverse problem of detecting solids moving in a fluid. It also includes, with slight modifications, more general situations of incomplete data (i.e. measurements on part of the outer boundary) or penetrable inhomogeneities. Our approach to tackle this type of problems is based on the derivation of a series expansion of the input-to-output map of the problem (typically the Dirichlet-to-Neumann map of the problem for the Calderón problem) in terms of the size of the obstacle.

3.3 Numerical analysis and simulation of heterogeneous systems

Within the team, we have developed in the last few years numerical codes for the simulation of FSIS and CWS. We plan to continue our efforts in this direction.

- In the case of FSIS, our main objective is to provide computational tools for the scientific community, essentially to solve academic problems.
- In the case of CWS, our main objective is to build tools general enough to handle industrial problems. Our strong collaboration with Christophe Geuzaine's team in Liège (Belgium) makes this objective credible, through the combination of DDM (Domain Decomposition Methods) and parallel computing.

Below, we explain in detail the corresponding scientific program.

- **Simulation of FSIS:** In order to simulate fluid-structure systems, one has to deal with the fact that the fluid domain is moving and that the two systems for the fluid and for the structure are strongly coupled. To overcome this free boundary problem, three main families of methods are usually applied to numerically compute in an efficient way the solutions of the fluid-structure interaction systems. The first method consists in suitably displacing the mesh of the fluid domain in order to follow the displacement and the deformation of the structure. A classical method based on this idea is the A.L.E. (Arbitrary Lagrangian Eulerian) method: with such a procedure, it is possible to keep a good precision at the interface between the fluid and the structure. However, such methods are difficult to apply for large displacements (typically the motion of rigid bodies). The second family of methods consists in using a *fixed mesh* for both the fluid and the structure and to simultaneously compute the velocity field of the fluid with the displacement velocity of the structure. The presence of the structure is taken into account through the numerical scheme. Finally, the third class of methods consists in transforming the set of PDEs governing the flow into a system of integral equations set on the boundary of the immersed structure. The members of SPHINX have already worked on these three families of numerical methods for FSIS systems with rigid bodies (see e.g. [112], [97], [113], [109], [110], [102]).

- **Simulation of CWS:** Solving acoustic or electromagnetic scattering problems can become a tremendously hard task in some specific situations. In the high frequency regime (i.e. for small wavelength), acoustic (Helmholtz's equation) or electromagnetic (Maxwell's equations) scattering problems are known to be difficult to solve while being crucial for industrial applications (e.g. in aeronautics and aerospace engineering). Our particularity is to develop new numerical methods based on the hybridization of standard numerical techniques (like algebraic preconditioners, etc.) with approaches borrowed from asymptotic microlocal analysis. Most particularly, we contribute to building hybrid algebraic/analytical preconditioners and quasi-optimal Domain Decomposition Methods (DDM) [63, 81], [82] for highly indefinite linear systems. Corresponding three-dimensional solvers (like for example GetDDM) will be developed and tested on realistic configurations (e.g. submarines, complete or parts of an aircraft, etc.) provided by industrial partners (Thales, Airbus). Another situation where scattering problems can be hard to solve is the one of dense multiple (acoustic, electromagnetic or elastic) scattering media. Computing waves in such media requires us to take into account not only the interactions between the incident wave and the scatterers, but also the effects of the interactions between the scatterers themselves. When the number of scatterers is very large (and possibly at high frequency [57, 58]), specific deterministic or stochastic numerical methods and algorithms are needed. We introduce new optimized numerical methods for solving such complex configurations. Many applications are related to this problem *e.g.* for osteoporosis diagnosis where quantitative ultrasound is a recent and promising technique to detect a risk of fracture. Therefore, numerical simulation of wave propagation in multiple scattering elastic media in the high frequency regime is a very useful tool for this purpose.

4 Application domains

4.1 Robotic swimmers

Some companies aim at building biomimetic robots that can swim in an aquarium, as toys but also for medical purposes. An objective of Sphinx is to model and to analyze several models of these robotic swimmers. For the moment, we focus on the motion of a nanorobot. In that case, the size of the swimmers leads us to neglect the inertia forces and to only consider the viscosity effects. Such nanorobots could be used for medical purposes to deliver some medicine or perform small surgical operations. In order to get a better understanding of such robotic swimmers, we have obtained control results via shape changes and we have developed simulation tools (see [71, 72, 102, 99]). Among all the important issues, we aim to consider the following ones:

1. Solve the control problem by limiting the set of admissible deformations.
2. Find the "best" location of the actuators, in the sense of being the closest to the exact optimal control.

The main tools for this investigation are the 3D codes that we have developed for simulation of fish in a viscous incompressible fluid (SUSHI3D) or in an inviscid incompressible fluid (SOLEIL).

4.2 Aeronautics

We will develop robust and efficient solvers for problems arising in aeronautics (or aerospace) like electromagnetic compatibility and acoustic problems related to noise reduction in an aircraft. Our interest for these issues is motivated by our close contacts with companies like Airbus or "Thales Systèmes Aéroportés". We will propose new applications needed by these partners and assist them in integrating these new scientific developments in their home-made solvers. In particular, in collaboration with C. Geuzaine

(Université de Liège), we are building a freely available parallel solver based on Domain Decomposition Methods that can handle complex engineering simulations, in terms of geometry, discretization methods as well as physics problems, see http://onelab.info/wiki/GetDDM.

5 New software and platforms

5.1 New software

5.1.1 BEC2HPC

Name: Bose-Einstein Condensates : Computation and HPC simulation

Keywords: Bose-Einstein condensates, HPC

Functional Description: Provide a flexible and efficient HPC software to the quantum physics community for simulating realistic problems.

URL: https://team.inria.fr/bec2hpc/software/

Contact: Xavier Antoine

6 New results

6.1 Control, stabilization and optimization of heterogeneous systems

Participants Rémi Buffe, Imene Djebour, Ludovick Gagnon, Julien Lequeurre, Jean-François Scheid, Takéo Takahashi, Julie Valein.

Control

Controlling coupled systems is a complex issue depending on the coupling conditions and the equations themselves. Our team has a strong expertise to tackle these kind of problems in the context of fluid-structure interaction systems. More precisely, we obtained the follwing results.

In [29], Jérôme Lohéac and Takéo Takahashi study the locomotion of a **ciliated microorganism in a viscous incompressible fluid**. They use the Blake ciliated model: the swimmer is a rigid body with tangential displacements at its boundary that allow it to propel in a Stokes fluid. This can be seen as a control problem: using periodical displacements, is it possible to reach a given position and a given orientation? They are interested in the minimal dimension d of the space of controls that allows the microorganism to swim. Their main result states the exact controllability with $d = 3$ generically with respect to the shape of the swimmer and with respect to the vector fields generating the tangential displacements. The proof is based on analyticity results and on the study of the particular case of a spheroidal swimmer.

In [34], M. Ramaswamy, A. Roy and T. Takahashi study the controllability of a **one-dimensional fluid-particle interaction model** where the fluid follows the viscous Burgers equation and the point mass obeys Newton's second law. They prove the null controllability for the velocity of the fluid and the particle and an approximate controllability for the position of the particle with a control variable acting only on the particle. One of the novelties of their work is the fact that they achieve this controllability result in a uniform time for all initial data and without any smallness assumptions on the initial data.

In [44], Imene Djebour shows the local null controllability of a **fluid-solid interaction system by using a distributed control located in the fluid**. The fluid is modeled by the incompressible Navier-Stokes system with Navier slip boundary conditions and the rigid body is governed by Newton's laws. Her main result yields that one can drive the velocities of the fluid and of the structure to 0 and one can control exactly the position of the rigid body. One important ingredient of the proof consists in a new Carleman estimate for a linear fluid-rigid body system with Navier boundary conditions.

Controlling a system with less inputs than equations is a hard task. In [21] this is successfully done for a system of **Korteweg-de Vries equations posed on an oriented tree shaped network**. The couplings and the controls appear only on boundary conditions.

Stabilization

Stabilization of infinite dimensional systems governed by PDE is a challenging problem. In our team, we have investigated this issue for different kinds of systems (fluid systems and wave systems) using different techniques.

In [45], Imene Djebour, Takéo Takahashi and Julie Valein consider the stabilization of parabolic systems with a finite-dimensional control subjected to a **constant delay**. Their main result shows that the Fattorini-Hautus criterion yields the existence of such a feedback control, as in the case of stabilization without delay. The proof consists in splitting the system into a finite dimensional unstable part and a stable infinite-dimensional part and in applying the Artstein transformation on the finite-dimensional system to remove the delay in the control. Using this abstract result, they can prove new results for the stabilization of parabolic systems with constant delay: the N-dimensional linear reaction-convection-diffusion equation with $N \geq 1$ and the Oseen system. They also show that this theory can be used to stabilize nonlinear parabolic systems with input delay: for instance the local feedback distributed stabilization of the Navier-Stokes system around a stationary state.

The aim of [55] is to study the asymptotic stability of the nonlinear Korteweg-de Vries equation in the presence of a **delayed term** in the internal feedback. First, the case where the weight of the term with delay is smaller than the weight of the term without delay is considered and a semiglobal stability result for any length is proved. Secondly, the case where the support of the term without delay is not included in the support of the term with delay is considered. In this case, a local exponential stability result is proved provided the weight of the delayed term is small enough. These results are illustrated by some numerical simulations. The above results on the stabilization of delay systems, added to other contributions on the control and stabilization of PDE constitute the material of the habilitation thesis [36] of Julie Valein, defended on November 4th 2020.

In [47], Ludovick Gagnon, Pierre Lissy and Swann Marx prove the exponential decay of a **degenerate parabolic equation**. The equation has a degeneracy at $x = 0$, which implies, roughly speaking, that the solution is "ill-propagated" near $x = 0$. The boundary controllability of this equation was already proved in a series of papers using a fine analysis of the spectral properties of the degenerate operator. The exponential stability proved in [47] is obtained by constructing a boundary feedback law using the backstepping method with a Fredholm transformation, yielding the exponential decay of the energy of the solutions. This work exhibits one of the first cases where the Fredholm transformation is used to deduce the exponential decay whereas the Volterra transformation couldn't be applied successfully.

In [26], a **one dimensional piston problem** is considered. It consists on the movement of a point mass in a compressible viscous gas. This problem is modeled by Newton's classical law coupled to the compressible Navier-Stokes equations in one dimension. J. Lequeurre proves the existence of global-in-time strong and weak solutions to this problem and the exponential decay of these solutions (in the corresponding function spaces) to an equilibrium chosen by acting on the piston with a constant force.

In [42], Rémi Buffe, Marcelo M. Cavalcanti, Valéria N. Domingos Cavalcanti and Ludovick Gagnon study the decay of the energy of a **wave propagating in two heterogeneous media**, with two different speeds of propagation, separated by a sharp interface. The sharp interface results in Snell's law of refraction of the wave propagating from one medium to another. A viscoelastic damping is also considered in one of the media. Under adequate assumptions, this damping decreases the energy of the system. This particular choice of damping, compared to the classical frictional damping, involves additional complications, as it is a memory term, that carries the past history of the wave. Using Dafermo's change of variables to define the proper decreasing energy, the exponential decay of the energy is proved under geometric assumptions on the support of the viscoelastic damping.

Optimization

We have also considered optimization issues for fluid-structure interaction systems.

J.F. Scheid, V. Calesti and I. Lucardesi study an **optimal shape problem** for an elastic structure immersed in a viscous incompressible fluid. They aim to establish the existence of an optimal elastic domain associated with an energy-type functional for a Stokes-Elasticity system. They want to find an optimal reference domain (the domain before deformation) for the elasticity problem that minimizes an energy-type functional. This problem is concerned with 2D geometry and is an extension of [115] for a 1D problem. The optimal domain is searched for in a class of admissible open sets defined with a diffeomorphism of a given domain. The main difficulty lies in the coupling between the Stokes problem written in a eulerian frame and the linear elasticity problem written in a lagrangian form. The shape derivative of an energy-type functional has been formally obtained. This will allow us to numerically determine an optimal elastic domain which minimizes the energy-type functional under consideration. The rigorous proof of the derivability of the energy-type functional with respect to the domain is still in progress.

In [25], T. Hishida, A.L. Silvestre and T. Takahashi consider a rigid body $\mathscr{S} \subset \mathbb{R}^3$ immersed in an infinitely extended Navier-Stokes liquid and the motion of the body-fluid interaction system described from a reference frame attached to $\mathscr{S}$. They are interested in steady motions of this coupled system, where the region occupied by the fluid is the exterior domain $\Omega = \mathbb{R}^3 \setminus \mathscr{S}$. More precisely, they consider the problem of using boundary controls v_*, acting on the whole $\partial\Omega$ or just on a portion Γ of $\partial\Omega$, to generate a self-propelled motion of $\mathscr{S}$ with a target velocity $V(x) := \xi + \omega \times x$ and to **minimize the drag** about $\mathscr{S}$. Firstly, an appropriate drag functional is derived from the energy equation of the fluid and the problem is formulated as an optimal boundary control problem. Then the minimization problem is solved for localized controls, such that supp $v_* \subset \Gamma$, and for tangential controls, i.e, $v_* \cdot n|_{\partial\Omega} = 0$, where n is the outward unit normal to $\partial\Omega$. They prove the existence of optimal solutions, justify the Gâteaux derivative of the control-to-state map, establish the well-posedness of the corresponding adjoint equations and, finally, derive the first order optimality conditions. The results are obtained under smallness restrictions on the objectives $|\xi|$ and $|\omega|$ and on the boundary controls.

6.2 Direct and inverse problems for heterogeneous systems

Participants Anthony Gerber-Roth, Alexandre Munnier, Julien Lequeurre, Karim Ramdani, Jean-Claude Vivalda.

Direct problems

Metamaterials (also called negative materials) are artificially structured composite materials whose dielectric permittivity and magnetic permeability are simultaneously negative in some frequency ranges. After publishing [69], K. Ramdani continued his collaboration with R. Bunoiu on the homogenization of composite materials involving both dielectric materials (positive materials) and metamaterials (negative materials). Due to the sign-changing coefficients in the equations, classical homogenization theory for scalar or vector Maxwell's systems fails, since it is based on uniform energy estimates which are known only for coefficients with constant sign. More precisely, a homogenization theory for such sign changing problems has been studied by Ramdani et al. in two papers.

- Reference [19] provides a homogenization result for Maxwell's system provided the dielectric and magnetic contrasts between the two materials (the positive and negative ones) is small or large enough. The analysis is based on a precise study of two associated scalar problems: one involving the sign-changing permittivity with Dirichlet boundary conditions, another involving the sign-changing permeability with Neumann boundary conditions. Let us emphasize that this work is the fruit of a collaboration with two colleagues from Inria Saclay, one from the Inria team DEFI and the other one from the group POEMS.
- In [43], K. Ramdani and his co-authors consider a geometrically degenerate scalar homogenization problem with sign changing coefficients. More precisely, they study a scalar problem in thin periodic composite media formed by two materials, a positive and a negative one. By applying T-coercivity methods and homogenization techniques specific to the thin periodic domains under consideration, they derive the homogenized limit problems, which exhibit dimension-reduction effects.

In [41], J.F. Scheid and M. Bouguezzi in collaboration with D. Hilhorst (Université Paris-Saclay) and Y. Miyamoto (University of Tokyo) prove the convergence of the solution of the one-phase Stefan problem in one-space dimension to a self-similar profile. The evolutional self-similar profile is viewed as a stationary solution of a Stefan problem written in a self-similar coordinates system. The proof of the convergence relies on the construction of sub and super-solutions for which it has been proved that they both tend to the same function. This limit function actually corresponds to the self-similar solution of the original Stefan problem.

In [53], A. Munnier investigates the asymptotics of Stokes and Navier-Stokes equations in a perforated domain as the size of the hole tends to 0. In particular, it is proved that eigenvalues of Stokes operator in such a geometry converge to those of the problem set in the domain without hole. For the Navier–Stokes equations, the vorticity is also shown to converge to the vorticity of the limit problem set in the punctured domain.

In [27], J. Lequeurre and A. Munnier propose a functional framework for the analysis of Navier-Stokes equations using vorticity or stream function formulations. For weak and strong problems, these formulations are proved to be equivalent to the classical ones.

Inverse problems

Alexandre Munnier and Karim Ramdani have obtained a PhD funding from Université de Lorraine to supervise the PhD of Anthony Gerber-Roth. The thesis is devoted to the investigation of some geometric inverse problems, and can be seen as a continuation of the work initiated by the two supervisors in [103] and [8]. In these papers, the authors addressed a particular case of Calderón's inverse problem in dimension two, namely the case of a homogeneous background containing a finite number of cavities (i.e. heterogeneities of infinitely high conductivities). They proposed a non iterative method to reconstruct the cavities from the knowledge of the Dirichlet-to-Neumann map of the problem. The first contribution of Anthony Gerber-Roth is to extend the results obtained in [8] in dimension three. This work is in progress.

Besides these static inverse problems, we also investigate estimation issues for time-dependent problems.

In [24], Jean-Claude Vivalda et al. consider a mathematical model of heat transfer in a direct contact membrane distillation used for the desalination of sea water. They first prove the well posedness of their model, then they design an observer, which is used to make an output tracking trajectory. In [11], Jean-Claude Vivalda et al. prove that the class of continuous-time systems which are strongly differentially observable after time sampling is open and dense (for the C^∞ topology) in the set of pairs (f,h) where f is a (parametrized) vector field given on a compact manifold and h is an observation function.

6.3 Numerical analysis and simulation of heterogeneous systems

Participants Xavier Antoine, Ismail Badia, David Gasperini, Christophe Geuzaine, Philippe Marchner, Jean-François Scheid.

Computational acoustics.

Artificial boundary conditions/PML. While high-order absorbing boundary conditions (HABC) are accurate for smooth fictitious boundaries, the precision of the solution drops in the presence of corners if no specific treatment is applied. In [31], the authors present and analyze two strategies to preserve the accuracy of Padé-type HABC at corners: first by using compatibility relations (derived for right angle corners) and second by regularizing the boundary at the corner. Exhaustive numerical results for two- and three-dimensional problems are reported in the paper. They show that using the compatibility relations is optimal for domains with right angles. For the other cases, the error still remains acceptable, but depends on the choice of the corner treatment according to the angle.

New stable PML (Perfectly Matched Layers) have been proposed in [30] for solving the convected Helmholtz equation for future industrial applications with Siemens (ongoing CIFRE Ph.D. thesis of Philippe Marchner).

Numerical approximation by volume methods. In [22], the authors propose a new high precision Iso-Geometric Analysis (IGA) B-Spline approximation of the high frequency scattering Helmholtz problem, which minimizes the numerical pollution effects that affect standard Galerkin finite element approaches when combined with HABC.

Domain decomposition. In [28], Xavier Antoine and his co-authors develop the first application of the optimized Schwarz domain decomposition method to aeroacoustics. Highly accurate three-dimensional simulations for turbofans are conducted through a collaboration with Siemens. In [32], an improved convergence of the domain decomposition method is obtained thanks to the newly designed absorbing boundary conditions proposed in [31] which are used as transmitting boundary conditions.

Integral equation approximation. In [20], a novel weak coupling technique is proposed for solving high frequency acoustic scattering problems by penetrable inhomogeneous media. These results were obtained during the CIFRE contract of the Ph.D. thesis of B. Caudron with Thalès. The industrialization of the method is currently being developed for Maxwell's equations during the Ph.D. thesis of I. Badia with Thalès (CIFRE contract).

In [12], an extensive review of recent methods for preconditioning fast integral equation solvers is mainly developed for time-harmonic acoustics, but also for electromagnetic and elastic waves.

Scattering by moving boundaries. A new frequency domain method has been introduced in [49] during the Ph.D. thesis of D. Gasperini to solve scattering problems by moving boundaries. This research was done during a contract with the company IEE (Luxembourg) for modeling the radar detection inside cars at very high frequency.

Underwater acoustics. New adiabatic pseudo-differential models as well as their numerical approximation are introduced in [33] for the simulation of the propagation of wave fields in underwater acoustics. In particular, the calculation of gallery modes is shown to be accurately obtained. This work is related to a new collaboration with P. Petrov from the V.I. Il'ichev Pacific Oceanological Institute, Vladivostok, Russia.

In [54], we develop an efficient second-order scheme with HABC for the one-dimensional Green-Naghdi equation that arises in water waves. We propose an adaptive method so that the accuracy of the scheme is maintained while strongly accelerating the speed-up, in particular because of the presence of a nonlocal time convolution-type operator involved in the HABC.

Quantum theory.

With E. Lorin, Xavier Antoine proposes in [15] an optimization technique of the convergence rate of relaxation Schwarz domain decomposition methods for the Schrödinger equation. This analysis is based on the use of microlocal analysis tools.

In [14], Xavier Antoine and his co-authors develop an implementation of the PML technique in the framework of Fourier pseudo-spectral approximation schemes for the fast rotating Gross-Pitaevskii equation. This is the first work related to the Inria associated team BEC2HPC. In [48], we give an overview of the BEC2HPC parallel solver developed in the BEC2HPC associated team for computing the stationary states of fast rotating BECs in 2D/3D. In [39], in collaboration with Q. Tang and J. Shen (Purdue University), we propose some new efficient spectral schemes for the dynamics of the nonlinear Schrödinger and Gross-Pitaevskii equations.

In [13], X. Antoine and his co-authors develop new Fourier pseudo-spectral schemes including a PML for the dynamics of the curved static Dirac equation. The goal is to be able to better understand quantum phenomena related to the charge carriers in strained graphene, with potential long term applications for designing quantum computers. This is a collaboration with E. Lorin (Carleton University), F. Fillion-Gourdeau and S. Mac Lean from the Institute for Quantum Computing, University of Waterloo.

In [40], X. Antoine and X. Zhao (Wuhan University) introduce some new locally smooth singular absorption profiles for the spectral numerical solution of the nonlinear Klein-Gordon equation. In particular, this leads to an accuracy of the scheme that does not depend on the small parameter arising in the non-relativistic regime. Applications are also given for the rotating Klein Gordon-equation used in the modeling of the cosmic superfluid in a rotating frame.

Fractional PDE.

In [50], with S. Ji, G. Pang, and J. Zhang, Xavier Antoine is interested in the development and analysis of artificial boundary conditions for nonlocal Schrödinger equations that are a generalization of some fractional Schrödinger equations.

The authors propose in [17] the construction and implementation of PML operators for the one- and two-dimensional fractional Laplacian, and some extensions.

In [16, 38], efficient linear algebra algorithms are built and tested for solving some classes of linear systems defined through functions. Applications are considered for fractional PDE.

In [37], a Schwarz waveform relaxation domain decomposition method has been introduced for solving space fractional PDE related to Schrödinger and heat equations.

Fluid mechanics.

Chaotic advection in a viscous fluid under an electromagnetic field. J.-F. Scheid, J.-P. Brancher (IECL) and J. Fontchastagner (GREEN) study the chaotic behavior of trajectories of a dynamical system arising from a coupling system beetwen Stokes flow and an electromagnetic field. They consider an electrically conductive viscous fluid crossed by a uniform electric current. The fluid is subjected to a magnetic field induced by the presence of a set of magnets. The resulting electromagnetic force acts on the conductive fluid and generates a flow in the fluid. According to a specific arrangement of the magnets surrounding the fluid, vortices can be generated and the trajectories of the dynamical system associated to the stationary velocity field in the fluid may have chaotic behavior. The aim of this study is to numerically show the chaotic behavior of the flow for the proposed disposition of the magnets along the container of the fluid. The flow in the fluid is governed by the Stokes equations with the Laplace force induced by the electric current and the magnetic field. An article is in preparation.

7 Bilateral contracts and grants with industry

7.1 Bilateral grants with industry

- Company: Siemens
- Duration: 2018 – 2021
- Participants: X. Antoine, C. Geuzaine, P. Marchner
- Abstract: This CIFRE grant funds the PhD thesis of Philippe Marchner, which concerns the numerical simulation of aeroacoustic problems using domain decomposition methods.

- Company: Thales
- Duration: 2018 – 2021
- Participants: X. Antoine, I. Badia, C. Geuzaine
- Abstract: This CIFRE grant funds the PhD thesis of Ismail Badia, which concerns the HPC simulation by domain decomposition methods of electromagnetic problems.

- Company: IEE
- Duration: 2018 – 2021
- Participants: X. Antoine, D. Gasperini, C. Geuzaine
- Abstract: This FNR grant funds the PhD thesis of David Gasperini, which concerns the numerical simulation of scattering problems with moving boundaries.

- Company: CEA
- Duration: May to September 2020
- Participants: A. Ouattara, J.-F. Scheid
- Abstract: This grant funds the internship of Abdoulaye Ouattara, which concerns the modelling and simulation of the propagation of pitting corrosion.

8 Partnerships and cooperations

8.1 International initiatives

8.1.1 Inria associate team not involved in an IIL

BEC2HPC

Title: *Bose-Einstein Condensates: Computation and HPC simulation*

Duration: 2019 - 2022

Coordinator: Xavier Antoine

Participants: Jérémie Gaidamour, Christophe Geuzaine, Qinglin Tang, Hanquan Wang, Yong Zhang

Partners:

- *College of Mathematics*, Sichuan University, Chengdu (China)

Inria contact: Xavier Antoine

Summary: All members of the associate team are experts in the mathematical modeling and numerical simulation of PDEs related to engineering and physics applications. The first objective of the associate team is to develop efficient high-order numerical methods for computing the stationary states and dynamics of Bose-Einstein Condensates (BEC) modeled by Gross-Pitaevskii Equations (GPEs). A second objective is to implement and validate these new methods in a HPC environment to simulate large scale 2D and 3D problems in quantum physics. Finally, a third objective is to provide a flexible and efficient HPC software to the quantum physics community for simulating realistic problems.

MOUSTIQ

Title: *Modeling and control of infectious diseases, wave propagation in heterogeneous media and nonlinear dispersive equations*

Duration: 2020 - 2023

Coordinator: Ludovick GAGNON

Participants: Takéo Takahashi, Julie Valein, Rémi Buffe, Swann Marx, Ademir Pazoto, Stefanella Boatto, Felipe Chaves, Fagner Araruna

Partners:

- *Mathematics Department*, Universidade Federale da Paraiba (Brazil)

Inria contact: Ludovick GAGNON

Summary: This project is divided into three research axes, all in the field of control theory and within the field of expertise of the Sphinx project team.

The first axis consists in improving a network transport model of virus spread by mosquitoes such as Zika, Dengue or Chikungunya. The objective is to introduce time-delay terms into the model to take into account delays such as incubation time or reaction time of health authorities. The study of the controllability of the model will then be carried out in order to optimize the reaction time as well as the coverage of the population in the event of an outbreak.

The second axis concerns the controllability of waves in a heterogeneous environment. These media are characterized by discontinuous propagation speed at the interface between two media, leading to refraction phenomena according to Snell's law. Only a few controllability results are known in restricted geometric settings, the last result being due to the Inria principal investigator. Examples of applications of the controllability of these models range from seismic exploration to the clearance of anti-personnel mines.

Finally, the last axis aims to study the controllability of nonlinear dispersive equations. These equations are distinguished by a decrease of the solutions due to the different propagation speed of each frequencies. Only few tools are available to obtain arbitrarily small time controllability results of these equations and many important questions remain open. These equations can be used to model, for example, the propagation of waves in shallow waters as well as the propagation of signals in an optical fiber.

8.2 National initiatives

ANR

- **Project Acronym :** IFSMACS
  Project Title : Fluid-Structure Interaction: Modeling, Analysis, Control and Simulation
  Coordinator: Takéo Takahashi
  Participants: Julien Lequeurre, Alexandre Munnier, Jean-François Scheid, Takéo Takahashi
  Duration : 48 months (started on October 1st, 2016)
  Other partners: Institut de Mathématiques de Bordeaux, Inria Paris (REO), Institut de Mathématiques de Toulouse
  Abstract: The aim of this project is to analyze systems composed by structures immersed in a fluid. Studies of such systems can be motivated by many applications (blood motion in veins, fish locomotion, design of submarines, etc.) but also by the corresponding challenging mathematical problems. Among the important difficulties inherent to these systems, one can quote nonlinearity, coupling and free-boundaries. Our objectives include asymptotic analyses of FSIS, the study of controllability and stabilizability of FSIS, the understanding of locomotion of self-propelled structures and the analysis and development of numerical tools to simulate fluid-structure systems.
  URL: `http://ifsmacs.iecl.univ-lorraine.fr/`

- **Project acronym:** ISDEEC
  Project title: Interaction entre Systèmes Dynamiques, Equations d'Evolution et Contrôle
  Coordinator: Romain Joly (Institut Fourier, Grenoble)
  Participant: Julie Valein
  Other partners: Institut Fourier, Grenoble; Département de Mathématiques d'Orsay
  Duration: 36 months (2017-2020)
  URL: `http://isdeec.math.cnrs.fr/`
  Abstract The aim of the project is to study the qualitative dynamics of various classes of PDEs and classes of ODEs with special structure. This work program requires expertise in different mathematical domains such as dynamical systems theory, PDE techniques, control theory, geometry, functional analysis... while the current trend in mathematics is for high specialisation. The purpose of this project is to create and extend interactions between experts of these various domains, in order to deepen our understanding of the dynamics of evolution equations and to explore the new challenging questions, which will emerge.

- **Project Acronym:** ODISSE
  Project title: Observer Design for Infinite-dimensional Systems
  Coordinator: Vincent Andrieu (LAGEPP, Université de Lyon)
  Local coordinator: Karim Ramdani
  Duration: 48 months (started on October 1st 2019)
  Participants: Ludovick Gagnon, Karim Ramdani, Julie Valein and Jean-Claude Vivalda.
  Other partners: LAAS, LAGEPP, Inria-Saclay (M3DISIM)
  Abstract: This ANR project includes 3 work-packages

  1. Theoretical aspects of observability and identifiability.
  2. From finite dimensional systems to infinite dimensional systems : Infinite-dimensional Luenberger observers, Parametric identification and adaptive estimation algorithm, Infinite-dimensional observers for finite-dimensional systems.
  3. From infinite dimensional systems to finite dimensional systems : discretization, hierarchical reduction.

- **Project Acronym :** TRECOS
  Project Title : New TREnds in COntrol and Stabilization

Coordinator: Sylvain Ervedoza (Université de Bordeaux)
Participants: Ludovick Gagnon, Takéo Takahashi, Julie Valein
Duration : 48 months (2021-2024)
Other partners: Institut de Mathématiques de Bordeaux, Sorbonne University, Institut de Mathématiques de Toulouse
Abstract: The goal of this project is to address new directions of research in control theory for partial differential equations, triggered by models from ecology and biology. In particular, our projet will deal with the development of new methods which will be applicable in many applications, from the treatment of cancer cells to the analysis of the thermic efficiency of buildings, and from control issues for the biological control of pests to cardiovascular fluid flows. **URL:** https://www.math.u-bordeaux.fr/~servedoza/index-ANR.html

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific Events: Organization

David Dos Santos Ferreira was the head of the Organization Committee of the national conference of the SMF (French Mathematical Society) that was scheduled in Nancy on 25th-29th may 2020. Unfortunately, this conference has been cancelled due to the coronavirus.

9.1.2 Journal

Member of the editorial boards Since 2018, Xavier Antoine is a member of the editorial board of "Multiscale in Science and Engineering (Springer)" and "International Journal of Computer Mathematics (Taylor and Francis)".

Reviewer - reviewing activities Members of the team often write reviews for many journals covering the topics investigated in SPHINX (SIAM Journals, JCP, M3AS, ESAIM COCV,...).

9.1.3 Scientific expertise

- Xavier Antoine is a member of the panel "Applied Mathematics and Statistics" of the Academy of Finland since February 2020.

9.1.4 Research administration

- Xavier Antoine was the Head of the Institut Elie Cartan de Lorraine laboratory until 31/08/2020.
- Ludovick Gagnon is International Deputy of Inria Nancy - Grand Est.
- Karim Ramdani was until the end of 2020 a board member of the RNBM (Réseau National des Bibliothèques de Mathématiques). He was in charge of Open Access issues (with Benoît Kloeckner). Since October 2018, he is also a member of the Working Group "Publications" of the national "Comité pour la Science Ouverte" of the French ministry of Higher Education, Research and Innovation. He was also a member of the hiring committee of an assistant professor at Polytech Nancy (Université de Lorraine).
- Julie Valein is a co-organizer of the weekly seminar of the PDE team of the Institut Elie Cartan de Lorraine in Nancy, since September 2018. She was also a member of the hiring committee of an assistant professor at Polytech Nancy (Université de Lorraine).

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

Except L. Gagnon, K. Ramdani, T. Takahashi and J.-C. Vivalda, SPHINX members have teaching obligations at "Université de Lorraine" and are teaching at least 192 hours each year. They teach mathematics at different level (Licence, Master, Engineering school). Many of them have pedagogical responsibilities.

9.2.2 Supervision

The following PhD was defended this year:

- I. Djebour, Controlability and stabilization of fluid-structure interaction problems, (started in November 2017 and defended in December 2020), supervised by T. Takahashi.

The following PhD are in progress:

- I. Badia, HPC simulation by domain decomposition methods of electromagnetic problems, (started in September 2019), supervised by X. Antoine and Ch. Geuzaine.
- D. Gasperini, Design of a new multi-frequency PDE-based approach for the numerical simulation of the Doppler effect arising in acoustic and electromagnetism (started in September 2017), supervised by X. Antoine and C. Geuzaine.
- A. Gerber-Roth, On some geometric inverse problems (started in October 2020), supervised by A. Munnier and K. Ramdani.
- P. Marchner, Numerical simulation by domain decomposition methods of aeroacoustic problems (started in September 2019), supervised by X. Antoine and C. Geuzaine.

9.2.3 Juries

- Xavier Antoine reviewed the PhD theses of G. Nehmetallah (Université de Nice, December 2020) and P. Payen (Université de Paris 13, December 2020).
- Karim Ramdani was a member of the PhD jury of I. Djebour (Université de Lorraine, December 2020) and a member of the HDR jury of J. Valein (Université de Lorraine, November 2020).
- Julie Valein was a member of the PhD jury of Nahed Naceur (Université de Lorraine, December 2020).
- Jean-Claude Vivalda was a member of the PhD jury of Basma Zitouni defended on 29 December 2020 at the University of Sfax (Tunisia).

10 Scientific production

10.1 Major publications

[1] X. Antoine, Q. Tang and J. Zhang. 'On the numerical solution and dynamical laws of nonlinear fractional Schrödinger/Gross-Pitaevskii equations'. In: *Int. J. Comput. Math.* 95.6-7 (2018), pp. 1423–1443. DOI: 10.1080/00207160.2018.1437911. URL: https://doi.org/10.1080/00207160.2018.1437911.

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10.2 Publications of the year

International journals

[11] S. Ammar, J.-C. Vivalda and B. Zitouni. 'Strong differential observability for sampled systems'. In: *SIAM Journal on Control and Optimization* 58.6 (Dec. 2020), pp. 3814–3841. DOI: 10.1137/19M1302867. URL: https://hal.inria.fr/hal-02377400.

[12] X. Antoine and M. Darbas. 'An introduction to operator preconditioning for the fast iterative integral equation solution of time-harmonic scattering problems'. In: *Multiscale Science and Engineering* (2021). DOI: 10.1007/s42493-021-00057-6. URL: https://hal.archives-ouvertes.fr/hal-02914922.

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[36] J. Valein. ‘Contrôle, stabilité et problèmes inverses pour les systèmes à retard et les réseaux : une contribution mathématique et numérique’. Université de Lorraine, 4th Nov. 2020. URL: https://hal.archives-ouvertes.fr/tel-03008177.

Reports & preprints

[37] X. Antoine and E. Lorin. *A Schwarz waveform relaxation method for time-dependent space fractional Schrödinger/heat equations*. 24th Jan. 2021. URL: https://hal.archives-ouvertes.fr/hal-03119456.

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