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Activity Report 2019

Project-Team SPHINX

Heterogeneous Systems: Inverse Problems, Control and Stabilization, Simulation

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

RESEARCH CENTER
Nancy - Grand Est

THEME
Optimization and control of dynamic systems

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Project-Team SPHINX

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2. Overall Objectives

2.1. 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 systems, 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 [119], [114], [94], 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], [73], [112], [83], [88], [116], [118], [102], [86]). Many other FSIS have been studied as well. Let us mention [104], [91], [87], [76], [64], [82], [65], [84] 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: [69], [64], [97], [78], [67]). Without approximations, the only known results [74], [75] 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 ([110]). 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 [92], [66], [106].

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 [93] or Kaltenbacher, Neubauer, and Scherzer [95]). 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 dependence 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 leads to investigate 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 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], [85], [89], [115] for the design of feedback controllers), an input (for instance source inverse problems [56], [68], [79]) 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 ([72]), specific one-dimensional techniques (like in [60]) or observer-based methods as in [100].

   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 [99], 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 [103] or [117]). Using observers, we have proposed in [105], [90] 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. [109], [96], [111], [107], [108], [101]).
- **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], [80], [81] 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 [58], [57]), 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 in the motion of a nanorobot. In that case, the size of the swimmers leads to neglect the inertia forces and to only consider the viscosity effects. Such nanorobots could be used for medical purposes to introduce 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], [70], [101], [98]). 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 a 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. Highlights of the Year

5.1. Highlights of the Year

Four members of the team are involved in the scientific project ODISSE funded by the ANR (october 2019-october 2023). The goal of this project, which gathers researchers from communities of automatic control and applied mathematics, is to investigate inverse problems using observer techniques.

6. New Software and Platforms

6.1. GetDDM

KEYWORDS: Large scale - 3D - Domain decomposition - Numerical solver

FUNCTIONAL DESCRIPTION: GetDDM combines GetDP and Gmsh to solve large scale finite element problems using optimized Schwarz domain decomposition methods.

- Contact: Xavier Antoine
- URL: http://onelab.info/wiki/GetDDM

6.2. GPELab

Gross-Pitaevskii equations Matlab toolbox

KEYWORDS: 3D - Quantum chemistry - 2D

FUNCTIONAL DESCRIPTION: GPELab is a Matlab toolbox developed to help physicists for computing ground states or dynamics of quantum systems modeled by Gross-Pitaevskii equations. This toolbox allows the user to define a large range of physical problems (1d-2d-3d equations, general nonlinearities, rotation term, multi-components problems...) and proposes numerical methods that are robust and efficient.

- Contact: Xavier Antoine
- URL: http://gpelab.math.cnrs.fr/

7. New Results

7.1. Control, stabilization and optimization of heterogeneous systems

Participants: Rémi Buffe, Thomas Chambrion, Eloïse Comte, Arnab Roy, Takéo Takahashi, Jean-François Scheid, Julie Valein.

Control and optimization

The use of measures (instead of functions) as controls is usually referred to as “impulsive control”. While the theory is now well understood for finite dimensional dynamics, many questions are still open for the control of PDEs. In [19], Thomas Chambrion and his co-authors discuss the notion of solution for the impulsive control (using measures instead of functions for the control) of the general bilinear Schrödinger equations. The results are adapted in [35] to the case of potentials with high regularity. These techniques have been used to extend the celebrated obstruction to controllability by Ball, Marsden and Slemrod to the case of abstract bilinear equations with bounded potentials [33] and the Klein-Gordon equation [20]. Other obstructions to controllability (preservation of regularity) have been investigated for the Gross-Pitaiewski equation with unbounded potentials [34].

In [15], an optimal control problem for groundwater pollution due to agricultural activities is considered, the objective being the optimization of the trade-off between the fertilizer use and the cleaning costs. The spread of the pollution is modeled by a convection-diffusion-reaction equation. We are interested in the buffer zone around the captation well and we determine its optimal size.

In [44], Eduardo Cerpa, Emmanuelle Crépeau and Julie Valein study the boundary controllability of the Korteweg-de Vries equation on a tree-shaped network, with less controls than equations.

In [27], 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 [31], Arnab Roy and Takéo Takahashi study the controllability of a fluid-structure interaction system. They consider a viscous and incompressible fluid modeled by the Boussinesq system and the structure is a rigid body with arbitrary shape which satisfies Newton’s laws of motion. They assume that the motion of this system is bidimensional in space. They prove the local null controllability for the velocity and temperature of the fluid and for the position and velocity of the rigid body for a control acting only on the temperature equation on a fixed subset of the fluid domain.

Rémi Buffe and Ludovick Gagnon consider N manifolds without boundary that intersect each other. They assume that the speed of propagation on each manifold is different, which implies that the Snell conditions applies at the interface. They give sufficient geometric conditions to ensure the controllability with distributed controls on $N - 1$ manifolds.

Stabilization

In [17], Lucie Baudouin, Emmanuelle Crépeau and Julie Valein study the exponential stability of the nonlinear Korteweg-de Vries equation with boundary time-delay feedback. Two different methods are employed: a Lyapunov functional approach (allowing to have an estimation on the decay rate, but with a restrictive assumption on the length of the spatial domain of the KdV equation) and an observability inequality approach, with a contradiction argument (for any non-critical lengths but without estimation on the decay rate).

In [55], Julie Valein shows the semi-global exponential stability of the nonlinear Korteweg-de Vries equation in the presence of a delayed internal feedback, for any lengths, in the case where the weight of the feedback with delay is smaller than the weight of the feedback without delay. In the case where the support of the feedback without delay is not included in the support of the feedback with delay, a local exponential stability result is proved if the weight of the delayed feedback is small enough.

Optimization

J.F. Scheid, V. Calesti (PhD Student) and I. Lucardesi study an optimal shape problem for an elastic structure immersed in a viscous incompressible fluid. They want to establish the existence of an optimal elastic domain associated with an energy-type functional for a Stokes-Elasticity system. We 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 the work of [113] for a 1D problem. The optimal domain is seeking in a class of admissible open sets defined with a diffeomorphism of a given domain. The main difficulty lies on 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 the energy-type functional is also aimed to be determined in order to numerically obtain an optimal elastic domain. This work is in progress.

7.2. Direct and Inverse problems for heterogeneous systems

Participants: Rémi Buffe, Imene Djebour, David Dos Santos Ferreira, Ludovick Gagnon, Alexandre Munnier, Julien Lequeurre, Karim Ramdani, Takéo Takahashi, Jean-Claude Vivalda.

Direct problems

In [22], Imene Djebour and Takéo Takahashi consider a fluid–structure interaction system composed by a three-dimensional viscous incompressible fluid and an elastic plate located on the upper part of the fluid boundary. They use here Navier-slip boundary conditions instead of the standard no-slip boundary conditions. The main results are the local in time existence and uniqueness of strong solutions of the corresponding system and the global in time existence and uniqueness of strong solutions for small data and if one assumes the presence of frictions in the boundary conditions.

In [42], Mehdi Badra (University of Toulouse) and Takéo Takahashi analyze a bi-dimensional fluid-structure interaction system composed by a viscous incompressible fluid and a beam located at the boundary of the fluid domain. The main result is the existence and uniqueness of strong solutions for the corresponding coupled system. The proof is based on a the study of the linearized system and a fixed point procedure. In particular, they show that the linearized system can be written with a Gevrey class semigroup. The main novelty with respect to previous results is that they do not consider any approximation in the beam equation.

In [18], Muriel Boulakia (Sorbonne University), Sergio Guerrero (Sorbonne University) and Takéo Takahashi consider a system modeling the interaction between a viscous incompressible fluid and an elastic structure. The fluid motion is represented by the classical Navier–Stokes equations while the elastic displacement is described by the linearized elasticity equation. The elastic structure is immersed in the fluid and the whole system is confined into a general bounded smooth three-dimensional domain. The main result is the local in time existence and uniqueness of a strong solution of the corresponding system.

In [28], Debayan Maity (TIFR Bangalore), Jorge San Martin (University of Chile), Takéo Takahashi and Marius Tucsnak (University of Bordeaux) study the interaction of surface water waves with a floating solid constraint to move only in the vertical direction. They propose a new model for this interaction, taking into consideration the viscosity of the fluid. This is done supposing that the flow obeys a shallow water regime (modeled by the viscous Saint-Venant equations in one space dimension) and using a Hamiltonian formalism. Another contribution of this work is establishing the well-posedness of the obtained PDEs/ODEs system in function spaces similar to the standard ones for strong solutions of viscous shallow water equations. Their well-posedness results are local in time for any initial data and global in time if the initial data are close (in appropriate norms) to an equilibrium state. Moreover, they show that the linearization of the system around an equilibrium state can be described, at least for some initial data, by an integro-fractional differential equation related to the classical Cummins equation and which reduces to the Cummins equation when the viscosity vanishes and the fluid is supposed to fill the whole space. Finally, they describe some numerical tests, performed on the original nonlinear system, which illustrate the return to equilibrium and the influence of the viscosity coefficient.

In [30], Benjamin Obando and Takéo Takahashi consider the motion of a rigid body in a viscoplastic material. This material is modeled by the 3D Bingham equations, and the Newton laws govern the displacement of the rigid body. The main result is the existence of a weak solution for the corresponding system. The weak formulation is an inequality (due to the plasticity of the fluid), and it involves a free boundary (due to the motion of the rigid body). They approximate it by regularizing the convex terms in the Bingham fluid and by using a penalty method to take into account the presence of the rigid body.

In [23], Alexandre Munnier and his co-authors consider the dynamics of several rigid bodies immersed in a perfect incompressible fluid. We show that this dynamics can be modelized by a second order ODE whose coefficients depend on the vorticity and the circulation of the fluid around the bodies. This formulation permits to point out the geodesic nature of the solutions, the added mass effect, the gyroscopic effects and the Kutta-Joukowski-type lift forces.

In [24], Julien Lequeurre and his co-authors study an unsteady nonlinear fluid–structure interaction problem. We consider a Newtonian incompressible two-dimensional flow described by the Navier-Stokes equations set in an unknown domain depending on the displacement of a structure, which itself satisfies a linear wave equation or a linear beam equation. The fluid and the structure systems are coupled via interface conditions prescribing the continuity of the velocities at the fluid–structure interface and the action-reaction principle. We prove existence of a unique local in time strong solution. In the case of the wave equation or a beam equation with inertia of rotation, this is, to our knowledge the first result of existence of strong solutions for which no viscosity is added. One key point, is to use the fluid dissipation to control, in appropriate function spaces, the structure velocity.

J.F. Scheid and M. Bouguezzi (PhD student) in collaboration with D. Hilhorst and Y. Miyamoto work on 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 must be proved that they both tend to the same function. It remains to show that this limiting function actually corresponds to the self-similar solution of the original Stefan problem. This work is in progress.

Rémi Buffe, Ludovick Gagnon *et al.* obtain the exponential decay of the solutions of coupled wave equations with a transmission condition at the interface and with a viscoelastic damping term. They prove that the exponential decay is obtained if the support of the viscoelastic term satisfies the uniform escaping geometry condition. They also deal with the case where the damping term touches the interface.

Inverse problems

In [43], the authors are interested in the homogenization of time-harmonic Maxwell's equations in a composite medium with periodically distributed small inclusions of a negative material. Here a negative material is a material modelled by negative permittivity and permeability. Due to the sign-changing coefficients in the equations, it is not straightforward to obtain uniform energy estimates to apply the usual homogenization techniques. 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. For both problems, we obtain a criterion on the physical parameters ensuring uniform invertibility of the corresponding operators as the size of the inclusions tends to zero. Then we use the results obtained for the scalar problems to derive uniform energy estimates for Maxwell's system.

In [37], Jean-Claude Vivalda and his co-authors prove that the class of continuous-time systems who are strongly differentially observable after time sampling is everywhere dense 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.

In [47], using a partial boundary measurement, Jean-Claude Vivalda and his co-authors design an observer for a system that models a desalination device; this observer being used to make an output tracking trajectory.

Rémi Buffe, David Dos Santos Ferreira and Ludovick Gagnon obtain an estimate on the magnetic Laplacian with sharp dependance on the power of the zeroth and first order potential and close to sharp norm of these potentials. This estimate is related to the observability inequality for the wave equation and to the cost of the control.

7.3. Numerical analysis and simulation of heterogeneous systems

Participant: Xavier Antoine.

Acoustics

Artificial boundary conditions: while high-order absorbing boundary conditions (HABCs) are accurate for smooth fictitious boundaries, the precision of the solution drops in the presence of corners if no specific treatment is applied. In [29], the authors present and analyze two strategies to preserve the accuracy of Padé-type HABCs at corners: first by using compatibility relations (derived for right angle corners) and second by regularizing the boundary at the corner. 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.

Domain decomposition : in [49], 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 (ongoing CIFRE Ph.D. Thesis of Philippe Marchner). In [26], the authors propose a new high precision IGA B-Spline approximation of the high frequency scattering Helmholtz problem, which minimizes the numerical pollution effects that affect standard Galerkin finite element approaches.

Underwater acoustics

New adiabatic pseudo-differential models as well as their numerical approximation are introduced in [53] 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.

Quantum theory

With E. Lorin, Xavier Antoine proposes in [13] 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. Convergence proofs are given in [11] for the real-time Schrödinger equation with optimized transmission conditions. We extend these results to the case of multiple subdomains in [13].

In [52], the authors analyze the convergence and stability in of a discretization scheme for the linear Schrödinger equation with artificial boundary conditions.

In [39], 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 international Inria team BEC2HPC, associated with China (https://team.inria.fr/bec2hpc/).

In [12], Antoine and his co-authors develop new Fourier pseudo-spectral schemes including a PML for the dynamics of the Dirac equation. The implementation of the method leads to the possibility of simulating complex quantum situations. In [38], the authors extend the approximation to 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.

Fractional PDE

In [32], with J. Zhang and D. Li, Xavier Antoine is interested in the development and analysis of fast second-order schemes to simulate the nonlinear time fractional Schrödinger equation in unbounded domains.

The authors propose in [14] the construction of PML operators for a large class of space fractional PDEs in one- and two-dimensions. The specific case of the fractional laplacian is carefully considered.

Xavier Antoine and Emmanuel Lorin are interested in [40] in the problem of building fast and robust linear algebra algorithms based on the discretization of the Cauchy integral formula used to represent the power matrix. Applications related to stationary PDEs are presented, with possibly randomly perturbed potentials. Differential doubly preconditioned iterative schemes are investigated in details in [41] to evaluate the power, and more generally functions, of matrices.

Error estimates of a semi-implicit ALE scheme for the one-phase Stefan problem. J.F. Scheid, M. Bouguezzi (PhD student) and D. Hilhorst study the convergence with error estimates of an Arbitrary-Lagrangian-Eulerian (ALE) scheme for the classical one-phase Stefan problem. Despite Stefan problems as well as ALE techniques are well-known in the mathematical litterature for many decades, surprisingly there is no global result on convergence (with error estimates) for fully space-time discretized scheme based on ALE formulations. The main difficulty lies on the unbounded behavior of the exact (and approximate) free boundary. Stability results have already been obtained for a time-discretized scheme (and continuous in space) for the one-space dimension case.

Chaotic advection in a viscous fluid under an electromagnetic field. J.F. Scheid, J.P. Brancher and J. Fontchastagner 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.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

Since September 2019, X. Antoine has been the co-advisor (with C. Geuzaine from Liège university) of two PhD theses, which are funded respectively by Siemens and Thales (CIFRE contracts).The aim of the first thesis is the numerical simulation by domain decomposition methods of aeroacoustic problems; the aim of the second one is the HPC simulation by domain decomposition methods of electromagnetic problems.

Zhanhao Liu works on a PhD thesis funded by Saint Gobain Recherche about the use of statistical methods for the effective control of industrial plants.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. 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 (starting on October 1st, 2016)
  Other partners: Institut de Mathématiques de Bordeaux, Inria Paris, 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 (motion of the blood 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, 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 analyze and development of numerical tools to simulate fluid-structure system.
  URL: http://ifsmacs.iecl.univ-lorraine.fr/
- **Project Acronym:** QUACO
  Project title: QUAntum COntrol: PDE systems and MRI
  Coordinator: Thomas Chambrion
  Duration: 48 months (starting January 1st 2018).
  URL: http://www.iecl.univ-lorraine.fr/~Thomas.Chambrion/QUACO/index.html
  Abstract The aim of the project is the use of geometrical tools for the study and the control of quantum system with application to MRI.
- **Project acronym:** ISDEEC
  Project title: Interaction entre Systèmes Dynamiques, Equations d'Evolution et Contrôle
  Coordinator: Romain Joly
  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
  Local coordinator: Karim Ramdani
  Duration: 48 months (starting on October 1st 2019)
  Participants: Ludovick Gagnon, Karim Ramdani, Julie Valein and Jean-Claude Vivalda.
  Other partners: Laas, Lagepp, Inria-Saclay
  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.

9.2. International Initiatives

9.2.1. Inria International Labs

9.2.1.1. BEC2HPC

Title: Bose-Einstein Condensates : Computation and HPC simulation

Head: Xavier Antoine

International Partner: Sichuan University, Chengdu (China) - Department of mathematics - Qinglin TANG

Start year: 2019

See also: https://team.inria.fr/bec2hpc/

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.

9.2.2. Participation in Other International Programs

9.2.2.1. Réseau Franco-Brésilien de mathématiques

Ludovick Gagnon collaborates with the Universidade Federal da Paraiba and Universidade Federal do Rio de Janeiro funded by the Réseau Franco-Brésilien de mathématiques.

9.2.2.2. Indo-French Center of Applied Mathematics

Title : **Analysis, Control and Homogenization of Complex Systems**

International Partner: TIFR CAM, Bangalore

Heads: Takéo Takahashi (France) and Mythily Ramaswamy (India).

Duration: 2018 - 2021

Scientific Objectives

- Study the well-posedness of models arising from either structure in the fluid or structure on the boundary of the domain containing the fluid.
- Explore Controllability, Optimal Control and Stabilization of such fluid-structure interaction problems.
- Study systems describing fluid flows in a time dependent domain with a rapidly oscillating boundary using Homogenization Theory. The rapid oscillations of the boundary takes into account, the rough character of the boundary and its movements may take into account the displacement of a deformable body into a fluid flow.
- Carry out Finite Element Analysis for such models, including elastic structures as well as rigid ones.

9.3. International Research Visitors

9.3.1. Visits to International Teams

Jean-François Scheid was invited to the “École Supérieure des Sciences et Technologie d’Hammam-Sousse”, Tunisia, 30 September–5 October 2019.

9.3.1.1. Research Stays Abroad

Xavier Antoine was invited to the Department of Mathematics, Sichuan University, Chengdu, January 2019 (2 weeks) + August 2019 (4.5 weeks) + November 2019 (3 weeks).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

- David Dos Santos Ferreira is the head of the Organization Committee of the next national conference of the SMF (French Mathematical Society) that will take place in Nancy from 25th-29th may 2020 (see: https://smf2020.math.cnrs.fr/).
- David Dos Santos Ferreira is, with Laurent Thomann, co-organizer of the national conference "Journées EDP". (see : http://jedp-2019.iecl.univ-lorraine.fr/).
- Julien Lequeurre and Alexandre Munnier are the heads of the national workshop "Journées EDP de l'Institut Elie Cartan de Lorraine" (see: http://journeesedp.iecl.univ-lorraine.fr/2019/).This an annual conference whose themes are those of the team PDE of the IECL (waves, fluid and fluid-structure interaction, form optimization,...).

10.1.1.2. Member of the Organizing Committees

- Karim Ramdani is a member of the Organizing Committee of the next national conference of the SMF (French Mathematical Society) (see: https://smf2020.math.cnrs.fr/).
- Thomas Chambrion was the organizer of the invited session "Analytic and Geometric Tools in Quantum Control", in the Conference on Decision and Control (CDC 2019, Nice, France).
- Ludovick Gagnon was an organizer of the CRAN/IECL day (November 22, 2019).
- Jean-François Scheid was a member of the organizing committee of the workshop "Journées Corrosion et Analyse Numérique", Laboratoire de Mathématiques d'Orsay, 4 – 5 July 2019.
- David Dos Santos Ferreira was a member of the scientific committee of the "Journées des Jeunes Edpistes Français", Rennes, 20-22 March 2019, https://jjedp19.sciencesconf.org/.

10.1.2. Scientific Events: Selection

10.1.2.1. Member of the Conference Program Committees

Xavier Antoine was a member of the scientific council of the international conference Waves 2019, Vienna, Austria, August, 2019.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Xavier Antoine is an associate editor of "Multiscale in Science and Engineering" (Springer) and "International Journal of Computer Mathematics" (Taylor and Francis);
- David Dos Santos Ferreira is a member of the editorial board of "Mathematical Control and Related Fields";
- Jean-Claude Vivalda is a member of the editorial board of the "Journal of Dynamical and Control System".

10.1.3.2. Reviewer - Reviewing Activities

Jean-Claude Vivalda is a reviewer for the "Mathematical reviews".

10.1.4. Invited Talks

- Rémi Buffe was an invited speaker at the “International itinerant workshop in PDEs” (Roma (Italy), February 2019).
- Rémi Buffe was an invited speaker at the “Journées Jeunes Contrôleurs” (Paris, June 2019).
- Rémi Buffe was an invited speaker at the “Conférence THESPEGE - Spectral Theory and Geometry”, (Seillac (France), September 2019).
- Thomas Chambrion took part to the invited session “Control of nonlinear PDEs” in Conference on Nonlinear Control Systems (NOLCOS 2019, Vienna (Austria)).
- Ludovick Gagnon was an invited speaker at the first Joint Meeting Brazil-France in Mathematics (Rio de Janeiro, July 2019).
- Jean-François Scheid was invited at the “Journées Corrosion et Analyse Numérique”, (Orsay, 4–5 July 2019).
- Jean-François Scheid was invited at the workshop “New Trends in Probability and Analysis” (NTPA), (Hammamet, Tunisia, 23–26 September 2019).
- Takéo Takahashi was an invited speaker at the congress VII MACI 2019, Río Cuarto (Argentina), May 2019.
- Takéo Takahashi was an invited speaker at the workshop PDE 2019, Berlin (Germany), September 2019.
- Takéo Takahashi was an invited speaker at the workshop “Franco-Brazilian meeting in mathematical fluid mechanics”, Lyon (France), October 2019.
- Takéo Takahashi was an invited speaker at the workshop “Feedback Control”, Linz (Austria), November 2019.

10.1.5. Leadership within the Scientific Community

David Dos Santos Ferreira is one of the coordinators of the GDR “Analyse des EDP”.

10.1.6. Research Administration

- Xavier Antoine is the director of the maths laboratory IECL and an elected member of the scientific council of the “Université de Lorraine”.
- Xavier Antoine was the president of the HCERES evaluation panel of the laboratory Lamav, (Valenciennes, February 2019). He was also a member of the HCERES evaluation panel of the “Fédération de Recherche des Hauts de France”, (February 2019).
- Xavier Antoine is the local coordinator of the France-Chinese CNRS LIASFMA in applied mathematics.
- David Dos Santos Ferreira is the treasurer of the SMF (French Mathematical Society).
- Karim Ramdani is member of the board of the RNBM (Réseau National des Bibliothèques de Mathématiques) and is 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.
- Ludovick Gagnon is International in charge of international relations for the Inria Nancy Grand-Est.
- Julie Valein was a member of the selection committee of new "maître de conférences" at “Université de Besançon-ISIFC” in April-May 2019.
- Julie Valein is a co-organizer of the “Séminaire EDP de l’Institut Elie Cartan de Lorraine, site de Nancy”.
- Julien Lequeurre is the organizer of the “Séminaire EDP de l’Institut Elie Cartan de Lorraine, site de Metz”.

10.2. Teaching - Supervision - Juries

10.2.1. 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.

Moreover, Julie Valein is a member of the managing board and of the selection committee of the engineer school “Polytech Nancy”, she is also a member of the “personnel commission” of IECL.

10.2.2. Supervision

- PhD in progress
  - I. Badia, HPC simulation by domain decomposition methods of electromagnetic problems, (started in september 2019), X. Antoine and Ch. Geuzaine.
  - I. Djebour, Controlability and stabilization of fluid-structure interaction problems, (started in November 2017), T. Takahashi.
  - D. Gasperini, design of a new multi-frequency PDE-based approach for the numerical simulation of the Doppler effect arising in acoustic and electromagnetism, X. Antoine.
  - Z. Liu, Statistical methods for the automatic generation of efficient command laws without model, April 2018, Th. Chambrion.
  - Ph. Marchner, Numerical simulation by domain decomposition methods of aeroacoustic problems, Sept. 2019, X. Antoine and Ch. Geuzaine.
  - Julie Valein is a member of the monitoring committee of the theses of Imène Djebour (september 2018 and 2019, advisor Takéo Takahashi) and Ibtissem Zaafrani (september 2019, advisor Simon Labrunie)

10.2.3. Juries

- Takéo Takahashi reviewed the PhD thesis of Jiao He, Université de Lyon, 2019.
- Xavier Antoine reviewed the PhD theses of
  - M. Averseng, Université de Saclay, 2019.
  - P. Mennuni, Université de Lille, 2019.
  - P. Marchand, Université de Sorbonne Université, 2020 (defense).
- Xavier Antoine reviewed the HDR of S. Chaillat, ENSTA, 2019.
- Jean-Claude Vivalda was a member of the thesis jury of Missie María del Rocío Aguado Rojas defended at June 2019 at “Centrale-Supélec”.
- David Dos Santos Ferreira was the president of the HDR thesis jury of Matthieu Léautaud (University of Paris Diderot).
- David Dos Santos Ferreira was a member of the HDR thesis jury of Thierry Daudé (University of Cergy-Pontoise).
- David Dos Santos Ferreira reviewed the PhD thesis of Cristóbal Meroño Moreno (Universidad Autónoma de Madrid)

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