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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

Contents

Project-Team SPHINX

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Keywords

Computer sciences and digital sciences

A6. – Modeling, simulation and control

A6.1. – Methods in mathematical modeling

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

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

A6.2.1. – Numerical analysis of PDE and ODE

A6.2.6. – Optimization

A6.2.7. – High performance computing

A6.3.1. – Inverse problems

A6.3.2. – Data assimilation

A6.4. – Automatic control

A6.4.1. – Deterministic control

A6.4.3. – Observability and Controlability

A6.4.4. – Stability and Stabilization

A6.5. – Mathematical modeling for physical sciences

A6.5.1. – Solid mechanics

A6.5.2. – Fluid mechanics

A6.5.4. – Waves

A6.5.5. – Chemistry

Other research topics and application domains

B2. – Health

B2.6. – Biological and medical imaging

B5. – Industry of the future

B5.6. – Robotic systems

B9. – Society and Knowledge

B9.5. – Sciences

B9.5.2. – Mathematics

B9.5.3. – Physics

B9.5.4. – Chemistry

1 Team members, visitors, external collaborators

Research Scientists

- Takéo Takahashi [Team leader, Inria, Senior Researcher, HDR]
- Ludovick Gagnon [Inria, Researcher]
- Karim Ramdani [Inria, Senior Researcher, HDR]
- Jean-Claude Vivalda [Inria, Senior Researcher, HDR]

Faculty Members

- Xavier Antoine [Univ de Lorraine, Professor, HDR]
- Rémi Buffe [Univ de Lorraine, Associate Professor]
- David Dos Santos Ferreira [Univ de Lorraine, Professor, HDR]
- Julien Lequeurre [Univ de Lorraine, Associate Professor]
- Alexandre Munnier [Univ de Lorraine, Associate Professor]
- Jean-François Scheid [Univ de Lorraine, Associate Professor, HDR]
- Julie Valein [Univ de Lorraine, Associate Professor, HDR]

Post-Doctoral Fellows

- Imene Djebour [Inria]
- Christophe Zhang [Inria, from Sep 2021]

PhD Students

- Ismail Badia [UDcast]
- Chorouq Bentayaa [Univ de Lorraine, from Oct 2021]
- Valentin Calisti [Univ de Lorraine, from Jun 2018 until Dec 2021]
- Blaise Colle [Inria, from Oct 2021]
- David Gasperini [Univ du Luxembourg]
- Anthony Gerber-Roth [Univ de Lorraine]
- Philippe Marchner [SIEMENS INDUSTRY SOFTWARE]

Interns and Apprentices

- Mouhamed Boye [Univ de Lorraine, from Jun 2021 until Sep 2021]
- Cédric Chane Ki Chune [Inria, from Jun 2021 until Sep 2021]
- Thomas Hélière [École des mines Nancy, from Jun 2021 until Aug 2021]
- Adrien Tendani Soler [Inria, from Apr 2021 until Jul 2021]

Administrative Assistant

- Céline Cordier [Inria]

External Collaborator

- Christophe Geuzaine [Univ de Liège]

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. **Direct problems**, that is finding a solution with respect to parameters of the problem, for instance the propagation of waves with respect to the knowledge of speed of propagation of the medium, 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. **Inverse problems** are the converse problem of the direct problems, as they aim to find properties of the direct problem, for instance the speed of propagation in a medium, with respect to the solution or a partial observation of the solution. These problems are often ill-posed and 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 [118, 112, 91], 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** ([73, 70, 110, 80, 85, 114, 117, 100, 83]). Many other FSIS have been studied as well. Let us mention [102, 88, 84, 74, 62, 79, 61, 81] 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: [66, 62, 94, 75, 64]). Without approximations, the only known results [71, 72] 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 ([107]). 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 [89, 63, 104].

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 [90] or Kaltenbacher, Neubauer, and Scherzer [92]). 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 [56, 82, 86, 113] for the design of feedback controllers), an input (for instance source inverse problems [53, 65, 76]) 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 ([69]), specific one-dimensional techniques (like in [57]) or observer-based methods as in [97].

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 [96], 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 [101] or [115]). Using observers, we have proposed in [103, 87] 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 [59, 58].

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. [108], [93], [109], [105], [106], [98]).

- **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) [60, 77], [78] 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 [54, 55]), 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 [67, 68, 98, 95]). 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 here.

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, Christophe Zhang.

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 [40], Badra and Takahashi consider the controllability of an **abstract parabolic system by using switching controls**. More precisely, we show that under general hypotheses, if a parabolic system is null-controllable for any positive time with N controls, then it is also null-controllable with the property that at each time, only one of these controls is active. The main difference with previous results in the literature is that we can handle the case where the main operator of the system is not self-adjoint. We give several examples to illustrate our result: coupled heat equations with terms of orders 0 and 1, the Oseen system or the Boussinesq system.

In [42], the authors prove an Hölder type inequality reflecting the unique continuation property at one time for the heat equation with a potential and Neumann boundary condition. The main feature of the proof is to overcome the propagation of smallness by a global approach using a refined parabolic frequency function method. It relies on a Carleman commutator estimate to obtain the logarithmic convexity property of the frequency function.

In [21], 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.

In [41], we prove a Lebeau-Robbiano spectral inequality for the **Oseen operator in a two dimensional channel**, that is, the linearized Navier-Stokes operator around a laminar flow, with no-slip boundary conditions. This is done by deriving a proper Carleman estimate by handling the vorticity near the boundary using two different characteristic sets in the different microlocal regions of the cotangent space. As a consequence of the spectral inequality, we derive a new estimate of the cost of the control for the small-time null-controllability.

In [43], we are interested in the controllability of a fluid-structure interaction system where the fluid is viscous and incompressible and where the structure is elastic and located on a part of the boundary of the fluid's domain. In this article, we simplify this system by considering a linearization and by replacing the wave/plate equation for the structure by a heat equation. We show that the corresponding system coupling the Stokes equations with a heat equation at its boundary is null-controllable. The proof is based on Carleman estimates and interpolation inequalities. One of the Carleman estimates corresponds to the case of Ventcel boundary conditions. This work can be seen as a first step to handle the real system where the structure is modeled by the wave or the plate equation.

The **convergence of numerical controls** for the wave equation is investigated for a Galerkin semi-discretization. The convergence of the numerical approximation for this equation is notoriously difficult as usual discretization schemes introduce spurious high frequencies. Filtering techniques are known in the literature for finite element methods. We introduced for the first time in [26] low cost filtering techniques for Galerkin approximations.

In [45], the controllability properties of the ground state solitary wave is studied for the **mass critical and subcritical focusing Schrödinger equation**. Using a fine description of the blow-up profile, Gagnon proves the local controllability between the ground state with two different scaling in a minimal time. This result provides insight on the technique needed to disrupt the stability of the ground state to gain controllability.

In [24], the dynamics of a **particle trapped on a network in presence of an external electromagnetic field** is adressed. The controllability of the motion is studied when the intensity of the field changes over time and plays the role of control. From a mathematical point of view, the dynamics of the particle is modeled by the so-called bilinear Schrödinger equation defined on a graph representing the network. The main purpose of this work is to extend the existing theory for bilinear quantum systems on bounded intervals to the framework of graphs. To this end, we introduce a suitable mathematical setting where to address the controllability of the equation from a theoretical point of view. More precisely, we determine assumptions on the network and on the potential field ensuring its global exact controllability in suitable spaces. Finally, we discuss two applications of our results and their practical implications to two specific problems involving a star-shaped network and a tadpole graph.

In [52], the **controllability properties of a system of m coupled Stokes systems or m coupled Navier-Stokes systems** are studied. The null-controllability of such systems is proved in the case where the coupling is in a cascade form and when the control acts only on one of the systems. Moreover, we impose that this control has a vanishing component so that we control a $m \times N$ state (corresponding to the velocities of the fluids) by $N-1$ distributed scalar controls. The proof of the controllability of the coupled Stokes system is based on a Carleman estimate for the adjoint system. The local null-controllability of the coupled Navier-Stokes systems is then obtained by means of the source term method and a Banach fixed point.

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 [48], Guerrero and Takahashi consider the controllability of a viscous incompressible fluid modeled by the Navier-Stokes system with a nonlinear viscosity. To prove the **controllability to trajectories**, we linearize around a trajectory and the corresponding linear system includes a nonlocal spatial term. Our main result is a Carleman estimate for the adjoint of this linear system. This estimate yields in a standard way the null controllability of the linear system and the local controllability to trajectories. Our method to obtain the Carleman estimate is completely general and can be adapted to other parabolic systems when a Carleman estimate is available.

In [22], 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 [36] 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 [116] of Julie Valein, defended on November 4th 2020.

In [25], 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 [25] 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 [46], the **backstepping method** with the Fredholm alternative is thoroughly studied for the Laplacian operator on the torus. A sharp functional setting is presented in this setting and the stabilization of the heat equation on the torus with two feedback laws is presented as an application.

In [44], Imene Djebour considers 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. The fluid motion is governed by the Navier-Stokes system whereas the structure displacement satisfies the damped plate equation. We consider here the Navier slip boundary conditions. The main result of this work is the **feedback stabilization of the strong solutions of the corresponding system around a stationary state** for any exponential decay rate by means of a time delayed control localized on the fixed fluid boundary. The strategy here is based on the Fattorini-Hautus criterion. Then, the main tool in this work is to show the unique continuation property of the associate solution to the adjoint system.

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 [111] 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.

The article [31] is devoted to the **mathematical analysis of a fluid-structure interaction system** where the fluid is compressible and heat conducting and where the structure is deformable and located on a part of the boundary of the fluid domain. The fluid motion is modeled by the compressible Navier-Stokes-Fourier system and the structure displacement is described by a structurally damped plate equation. Our main results are the existence of strong solutions in an $L_P - L_q$ setting for small time or for small data. Through a change of variables and a fixed point argument, the proof of the main results is mainly based on the maximal regularity property of the corresponding linear systems. For small time existence, this property is obtained by decoupling the linear system into several standard linear systems whereas for global existence and for small data, the maximal regularity property is proved by showing that the corresponding linear coupled fluid-structure operator is R-sectorial.

In [39], Badra and Takahashi consider a viscous incompressible fluid interacting with an elastic structure located on a part of its boundary. The fluid motion is modeled by the bi-dimensional Navier-Stokes system and the structure follows the linear wave equation in dimension 1 in space. Our aim is to study the linearized system coupling the Stokes system with a wave equation and to show that the corresponding semigroup is analytic. In particular the linear system satisfies a maximal regularity property that allows us to deduce the existence and uniqueness of strong solutions for the nonlinear system. This result can be compared to the case where the elastic structure is a beam equation for which the corresponding semigroup is only of Gevrey class.

6.2 Direct and inverse problems for heterogeneous systems

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

Direct problems

Negative materials are artificially structured composite materials (also known as metamaterials), whose dielectric permittivity and magnetic permeability are simultaneously negative in some frequency ranges. K. Ramdani continued his collaboration with R. Bunoiu on the homogenization of composite materials involving both positive and negative materials. Due to the sign-changing coefficients in the equations, classical homogenization theory fails, since it is based on uniform energy estimates which are known only for positive (more precisely constant sign) coefficients. In a joint work with L. Chesnel and M. Rihani, the authors studied [19] the vector case of Maxwell'es equations. In [20] and [35], both in collaboration with C. Timofte, two “degenerate” situations are respectively considered : the case of thin periodic domains and the one of extreme contrasts.

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 [99] 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.

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.

New stable PML (**Perfectly Matched Layers**) have been proposed in [33] 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 [23], 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.

In the papers [32, 34, 50], we build and evaluate some new absorbing boundary conditions for the heterogeneous Helmholtz equation, two-dimensional Schrödinger equation in the presence of corners and the 2D peridynamics equations based on kernel analysis, respectively.

In [51], we develop the numerical analysis of discretization schemes with absorbing boundary conditions for the one-dimensional Schrödinger equation where the Laplacian is replaced by a nonlocal spatial operator.

Integral equation approximation.

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.

In [11], we introduce a coupling algorithm between the integral equation and OSRC methods to solve scattering problems by non convex obstacles.

In [47], the mathematical analysis of the steepest descent methods is investigated for the acooustic single-layer integral operator.

Scattering by moving boundaries.

A new frequency domain method has been introduced in [29] 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.

In [28], we propose an original coupled frequency domain approach for solving by the finite element method the scattering problem with a moving boundary for two- and three-dimensional problems.

The paper [37] introduces a new OSRC formulaion with phase reduction and approximated by IGA-NURBS to solve time-harmonic acoustic scattering problems.

In [18], a weak coupling finite element/boundary element method is introduced for solving 3D electromagnetic scattering problems.

Underwater acoustics.

In [49], 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.

In [27], 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 [16], 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 [17], 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 [30], 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.

In [13, 14], the numerical computation of fractional linear systems involving several matrix power functions. We propose several gradient methods for solving these very computationally complex problems, which themselves require the solution to standard Fractional Linear Systems. The convergence study is developed and numerical experiments are proposed to illustrate and compare the methods.

The authors propose in [15] the construction and implementation of PML operators for the one- and two-dimensional fractional Laplacian, and some extensions.

In [38], 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

1. - 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.
2. - 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.

3.
- 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.

8 Partnerships and cooperations

8.1 International initiatives

8.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

MOUSTIQ

Title: Modelization and control of infectious diseases, wave propagation in heterogeneous media and nonlinear dispersives equations

Duration: 2022 ->

Coordinator: Felipe Chaves (felipewallison@gmail.com)

Partners:

- Universidade Federale da Paraiba, Brazil

Inria contact: Ludovick Gagnon

Summary: The aim of Moustiq is to include time delay in existing model for the propagation of diseases such as Zika, Dengue or Chikungunya. Other aspects of the project involve controllability issues of wave equations with dynamic boundary conditions and of nonlinear dispersive equations.

8.1.2 Inria associate team not involved in an IIL or an international program

BEC2HPC

Title: Bose-Einstein Condensates : Computation and HPC simulation

Duration: 2019 ->

Coordinator: Qinglin TANG (qinglin_tang@163.com)

Partners:

- Sichuan University, Chengdu, China

Inria contact: Xavier Antoine

Summary: 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.

8.1.3 STIC/MATH/CLIMAT AmSud project

ACIPDE

Title: Analysis, Control and Inverse problems for Partial Differential Equations

Duration: 2020 ->

Coordinators: Takéo Takahashi, Felipe Chaves-Silva (Brazil), Nicolas Carreño (Chile)

Partners:

- Brazil
- Chile

Members of SPHINX: Ludovick Gagnon, Takéo Takahashi, Julie Valein

8.1.4 Participation in other International Programs

LIAFSMA (CNRS International Research Project)

Title: Sino-French International Associated Laboratory for Applied Mathematics

Partner Institution(s):

- CNRS
- École Polytechnique
- Sorbonne Université
- Université de Bordeaux and Institut Polytechnique de Bordeaux
- The Fudan University, China
- The Peking University, China
- The Academy of Mathematics and System Sciences of the Chinese Academy of Sciences, China

Local coordinator: Xavier Antoine

ANR

1. **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 : theoretical aspects of observability and identifiability; 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; from infinite dimensional systems to finite dimensional systems : discretization, hierarchical reduction.

2. **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

Member of the organizing committees

- Julie Valein was a member of the organizing committee of the conference“PDE, Analysis and Application”, in honor of Serge Nicaise 60th birthday (Valenciennes, 2–5 November 2021).

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,...).

9.0.1 Invited talks

Karim Ramdani and Julie Valein were invited to give a talk in the conference “Control and analysis of PDE systems” in honor of Marius Tucsnak 60th birthday (Bordeaux, Nov. 29–Dec. 1 2021).

9.0.2 Scientific expertise

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

9.0.3 Research administration

- David Dos Santos Ferreira was the head of the PDE team of IECL until June 2021. He is also one of the coordinators of the CNRS GDR (National Research Network) “Analysis of PDE” and the treasurer of the SMF (French Mathematical Society).

- Ludovick Gagnon is International Deputy of Inria Nancy - Grand Est.

- Karim Ramdani is, since June 2021, the head of the PDE team of IECL laboratory (the Mathematics Department of Université de Lorraine). He is also a member (since October 2018) of the Working Group “Publications” of the “Committee for Open Science” of the French ministry of Higher Education, Research and Innovation.
- Several members of the team are involved in monitoring committees of PhDs students as well as the committee attributing PhD funding in IECL laboratory.
- Ludovick Gagnon and Julie Valein are the organizers of the weekly seminar of the PDE team of the Institut Elie Cartan de Lorraine in Nancy. Rémi Buffe is the organizer of the Groupe de Travail d’EDP of the Institut Elie Cartan de Lorraine.

9.1 Teaching - Supervision - Juries

9.1.1 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.

9.1.2 Supervision

The following PhD thesis was defended this year:

- V. Calisti, Synthèse de microstructures par optimisation topologique, et optimisation de forme d’un problème d’interaction fluide-structure, (started Aug 2018 and defended Dec 2021), supervised by Jean-François Scheid and Jean-François Ganghoffer.

The following PhD thesis 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.
- C. Bentayaa, Accurate and efficient computational methods for the HPC simulation of Bose-Einstein Condensates (started in October 2021), supervised by X. Antoine and Q. Tang
- B. Colle, Stabilization and controllability of the Stefan problem (started in October 2021), supervised by J. Lohéac and 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 (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.

9.1.3 Juries

- Ludovick Gagnon was member of the PhD thesis jury of G. Vergara-Hermosilla (Université de Bordeaux, Oct 2021).
- Takéo Takahashi was reviewer of the PhD thesis of G. Vergara-Hermosilla (Université de Bordeaux, Oct 2021).
- Julie Valein was president of the PhD thesis jury of Alaa Hayek (Université Polytechnique des Hauts-de-France - Université Libanaise, Fev 2021).
- Julie Valein was reviewer of the PhD thesis jury of Mathias Dus (Université de Toulouse, Jul 2021).

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. M. Alzahrani, X. Antoine and C. Chniti. 'A coupling between integral equations and on-surface radiation conditions for diffraction problems by non convex scatterers'. In: *Mathematics* 9.18 (2021). DOI: 10.3390/math9182299. URL: https://hal.archives-ouvertes.fr/hal-03327881.

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