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ACTIVITY REPORT

Project-Team

SPHINX

Heterogeneous Systems: Inverse Problems, Control and Stabilization, Simulation

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

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Optimization and control of dynamic systems

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Project-Team SPHINX

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2 Overall objectives

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

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

(CWS) Complex wave systems are involved in a large number of applications in several areas of science and engineering: medicine (breast cancer detection, kidney stone destruction, osteoporosis diagnosis, etc.), telecommunications (in urban or submarine environments, optical fibers, etc.), aeronautics (target detection, aircraft noise reduction, etc.) and, in the longer term, quantum supercomputers. **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 Analysis, control, stabilization and optimization of heterogeneous systems

Fluid-Structure Interaction System 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 [112, 107, 84], 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** ([66, 63, 105, 73, 78, 109, 111, 95, 76]). Many other FSIS have been studied as well. Let us mention [97, 81, 77, 67, 55, 72, 54, 74] 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: [59, 55, 87, 68, 57]). Without approximations, the only known results [64, 65] 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 ([102]). 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 [82, 56, 99].

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 [83] or Kaltenbacher, Neubauer, and Scherzer [85]). 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 [49, 75, 79, 108] for the design of feedback controllers), an input (for instance source inverse problems [46, 58, 69]) 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 ([62]), specific one-dimensional techniques (like in [50]) or observer-based methods as in [91].

   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 [89], 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 [96] or [110]). Using observers, we have proposed in [98, 80] 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 [52, 51].

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. [103], [86], [104], [100], [101], [92]).

- **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) [53, 70], [71] 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 [47, 48]), 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, such as 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 [60, 61, 92, 88]). 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 Highlights of the year

One of the members of the assessment panel that evaluated our team in 2021 wrote an email to the team leader wondering how it is possible that almost a year after he sent his report,he had still not received his honorarium. The problems due to the deployment of EKSAE (the new Inria Information System for finance and human resources) are detrimental to the people outside the institute who have agreed to collaborate with us. They also put us in a situation that is more than embarrassing, and damages the credibility of our institute. Finally, they are also detrimental to the staff of the institute by making them work in unacceptable conditions.

6 New software and platforms

6.1 New software

6.1.1 FlatStefan

Keyword: Control

Functional Description: This provides codes related to the paper "Controllability of the Stefan problem by the flatness approach" by Blaise Colle, Jérôme Lohéac and Takéo Takahashi (https://hal.science/hal-03721544Flatness).

URL: `https://hal.science/hal-03889209`

Publication: hal-03721544

Contact: Takeo Takahashi

Participants: Blaise Colle, Jérôme Lohéac, Takeo Takahashi

7 New results

7.1 Analysis, 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.

Analysis of fluid mechanics

In [18], we study a bi-dimensional viscous incompressible fluid in interaction with a beam located at its boundary. We show the existence of strong solutions for this fluid-structure interaction system, extending a previous result where they supposed that the initial deformation of the beam was small. The main point of the proof consists in the study of the linearized system and in particular in proving that the corresponding semigroup is of Gevrey class.

In [17], we 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. The aim of the article 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 ([18]) for which the corresponding semigroup is only of Gevrey class.

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 following results.

In [20], we prove an inequality of Hölder type traducing 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], 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.

In [33], we prove the null-controllability of the non-simplified fluid-structure system (as opposed to [21]), that is, a system coupling the Navier-Stokes equation for the fluid and a plate equation at the boundary. The control acts on arbitrary small subsets of the fluid domain and in a small subset of the vibrating boundary. By proving a proper observability inequality, we obtain the local controllability for the non-linear system. The proof relies on microlocal argument to handle the pressure terms.

In [25], an optimal control problem for the Navier–Stokes system with Navier slip boundary conditions is considered. Denoting by α the friction coefficient, we analyze the asymptotic behavior of such a problem as $\alpha \to \infty$. More precisely, we prove that for every $\alpha > 0$, there exists a sequence of optimal controls converging to an optimal control of a similar problem but for the Navier–Stokes system with the Dirichlet boundary condition. We also show the convergence of the corresponding direct and adjoint states.

In [35], we study the local null controllability of a modified Navier-Stokes system where they include nonlocal spatial terms. We generalize a previous work where the nonlocal spatial term is given by the linearization of a Ladyzhenskaya model for a viscous incompressible fluid. Here the nonlocal spatial term is more complicated and they consider a control with one vanishing component. The proof of the result is based on a Carleman estimate where the main difficulty consists in handling the nonlocal spatial terms. One of the key points is a particular decomposition of the solution of the adjoint system that allows us to overcome regularity issues. With a similar approach, we also show the existence of insensitizing controls for the same system.

In [36], we show the boundary controllability to stationary states of the Stefan problem with two phases and in one dimension in the space variable. For an initial condition that is a stationary state and for a time of control large enough, we also obtain the controllability to stationary states together with the sign constraints associated to the problem. Our method is based on the flatness approach that consists in writing the solution and the controls through two outputs and their derivatives. We construct these outputs as Gevrey functions of order σ so that their solution and controls are also in a Gevrey class.

In [39], we consider a nonlinear system of two parabolic equations, with a distributed control in the first equation and an odd coupling term in the second one. We prove that the nonlinear system is small time locally null-controllable. The main difficulty is that the linearized system is not null-controllable. To overcome this obstacle, we extend in a nonlinear setting the strategy introduced in a previous article that consists in constructing odd controls for the linear heat equation. The proof relies on three main steps. First, we obtain from the classical L^2 parabolic Carleman estimate, conjugated with maximal regularity results, a weighted L^p observability inequality for the nonhomogeneous heat equation. Secondly, we perform a duality argument, close to the well-known Hilbert Uniqueness Method in a reflexive Banach setting, to prove that the heat equation perturbed by a source term is null-controllable thanks to odd controls. The nonlinearity is handled with a Schauder fixed-point argument.

Finally, in [43], C. Zhang and co-authors consider the internal control of linear parabolic equations through on-off shape controls with a prescribed maximal measure. They establish small-time approximate controllability towards all possible final states allowed by the comparison principle with non negative controls and manage to build controls with constant amplitude.

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.

The work [24] is devoted to the stabilization of parabolic systems with a finite-dimensional control subjected to a constant delay. Our 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 to apply the Artstein transformation on the finite-dimensional system to remove the delay in the control. Using our abstract result, we can prove new results for the stabilization of parabolic systems with constant delay.

The aim of [31] is to study the asymptotic stability of the nonlinear Korteweg-de Vries equation in the presence of a delayed term. We first consider the case where the weight of the term with delay is smaller than the weight of the term without delay and we prove a semiglobal stability result for any lengths. Secondly we study the case where the support of the term without delay is not included in the support of the term with delay. In that case, we give a local exponential stability result if the weight of the delayed term is small enough. We illustrate these results by some numerical simulations.

In [42], we consider the Korteweg-de Vries equation with time-dependent delay on the boundary or internal feedbacks. Under some assumptions on the time- dependent delay, on the weights of the feedbacks and on the length of the spatial domain, we prove the exponential stability results, using appropriate Lyapunov functionals. We finish by some numerical simulations that illustrate the stability results and the influence of the delay on the decay rate.

In [32], we consider a wave equation with a structural damping coupled with an undamped wave equation located at its boundary. We prove that, due to the coupling, the full system is parabolic. In order to show that the underlying operator generates an analytical semigroup, we study in particular the effect of the damping of the "interior" wave equation on the "boundary" wave equation and show that it generates a structural damping.

In [38], we prove the rapid stabilization of the linearized water waves equation with the Fredholm backstepping method. This result is achieved by overcoming an important theoretical threshold imposed by the classical methodology, namely, the quadratically close criterion. Indeed, the spatial operator of the linearized water waves exhibit an insufficient growth of the eigenvalues and the quadratically close criterion is not true in this case. We introduce the duality compactness method for general skew-adjoint operators to circumvent this difficulty. In turn, we prove the existence of a Fredholm backstepping transformation for a wide range of equations, opening the path to an abstract framework for this widely used method.

In [37], I. Djebour investigates the stabilization of 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 main result of this paper 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.

Optimization

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

J.F. Scheid, V. Calisti 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 [106] 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 [90] 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 [17], we 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.

7.2 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 [23], in collaboration with C. Timofte, the authors investigate the homogenization of a diffusion-type problem, for sign-changing conductivities with extreme contrasts (of order ε^2, where ε is the period of the composite material). In [22], also in collaboration with C. Timofte, the case of imperfect interface conditions is considered, by allowing flux jumps across their oscillating interface. The main difficulties of this study are due to the sign-changing coefficients and to the appearance of an unsigned surface integral term in the variational formulation. A proof by contradiction (nonstandard in this context) and T-coercivity technics are used in order to cope with these difficulties.

Inverse problems

Supervised by Alexandre Munnier and Karim Ramdani, the PhD of Anthony Gerber-Roth 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 [94] and [93]. In these papers, the authors addressed a particular case of

Calderòn'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). The first contribution of Anthony Gerber-Roth was to apply the method proposed in [93] to tackle a two-dimensional inverse gravimetric problem. The strong connection with the important notion of quadrature domains in this context has been highlighted. An efficient reconstruction algorithm has been proposed (and rigorously justified in some cases) for this geometric inverse problem. This work, which is still in progress, has been presented to the conference WAVES 2022, the 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation.

In [34], an optimal shape problem for a general functional depending on the solution of a bidimensional Fluid-Structure Interaction problem (FSI) is studied. The system is composed by a coupling stationary Stokes-Elasticity sub-system for modeling the deformation of an elastic structure immersed in a viscous fluid. The differentiability with respect to reference elastic domain variations is proved under shape perturbations with diffeomorphisms. The shape-derivative is then calculated. The main difficulty for studying the shape sensitivity, lies in the coupling between the Stokes problem written in a Eulerian frame and the linear elasticity problem written in a Lagrangian form.

7.3 Numerical analysis and simulation of heterogeneous systems

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

The work in [19] is devoted to the long time behaviour of the solution of a one dimensional Stefan problem arising from corrosion theory. It is rigorously proved that under rather general hypotheses on the initial data, the solution of this free boundary problem converges to a self-similar profile as the time $t \to +\infty$. This convergence result is proved by applying a comparison principle together with suitable upper and lower solutions. Some numerical simulations illustrate this time asymptotic behavior.

The paper [13] is devoted to the numerical computation of fractional linear systems. The proposed approach is based on an efficient computation of Cauchy integrals allowing to estimate the real power of a (sparse) matrix A. A first preconditioner M is used to reduce the length of the Cauchy integral contour enclosing the spectrum of M A, hence allowing for a large reduction of the number of quadrature nodes along the integral contour. Next, ILU-factorizations are used to efficiently solve the linear systems involved in the computation of approximate Cauchy integrals. Numerical examples related to stationary (deterministic or stochastic) fractional Poisson-like equations are finally proposed to illustrate the methodology.

Several contributions have been devoted to the numerical approximation of problems set in unbounded domains, appearing in acoustics, electromagnetics, quantum field theory, fluid mechanics and continuum mechanics. More precisely, absorbing boundary conditions (ABC) have been used to solve acoustic scattering problems [28], the linearized Green-Naghdi system in fluid dynamics [29] and a mechanical problem from peridynamics [30]. Perfectly matched players (PML) have been proposed for the numerical solution of nonlinear Klein-Gordon equations [15]. In electromagnetics, coupling between high-order finite elements and boundary elements has been used to tackle time-harmonic scattering by inhomogeneous objects [16]. In acoustics, other methods have been also proposed: integral equations methods for 3D high-frequency acoustic scattering problems [27] and on-surface radiation conditions (OSRC) combined with isogeometric (IGA) finite elements [11]. Finally, the acoustic scattering problem by small-amplitude boundary deformations has been studied in [26] using a multi-harmonic finite element method.

In collaboration with Emmanuel Lorin, Xavier Antoine investigated numerical methods to tackle fractional equations, either in the PDE case [12, 13] or for algebraic linear systems [14].

8 Bilateral contracts and grants with industry

Participants: Xavier Antoine, Ismail Badia, David Gasperini, Christophe Geuzaine, Philippe Marchner.

8.1 Bilateral grants with industry

The three industrial PhD theses of I. Badia, D. Gasperini and P. Marchner have been defended in 2022.

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.

9 Partnerships and cooperations

Participants: Xavier Antoine, Ludovick Gagnon, Takéo Takahashi.

9.1 International initiatives

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

BEC2HPC

Title: Bose-Einstein Condensates : Computation and HPC simulation

Duration: 2019 - 2022

Coordinator: Qinglin TANG

Partners:

- Sichuan University, Chengdu (Chine)

Inria contact: Xavier Antoine

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

MOUSTIQ

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

Duration: 2020 - 2024

Coordinator: Felipe Chaves (Assistant professor, Departamento de Matemática of Universidade Federal da Paraíba)

Partners:

- Universidade Federale da Paraiba (Brésil)

Inria contact: Ludovick Gagnon

Summary: This project is divided into three research axes, all in the field of control theory and within the field of expertise of the Sphinx project team. Although covering several fields of applications, the problems studied here can be handled with similar mathematical techniques.

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

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

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

9.1.2 STIC/MATH/CLIMAT AmSud projects

ACIPDE

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

Program: MATH-AmSud

Duration: January 1, 2020 – December 31st, 2023

Local supervisor: Takéo Takahashi

Partners:

- Federal University of Paraiba
- Carreno (Chili)

Inria contact: Takeo Takahashi

Summary: The objective of this project is two-folded. On one hand, we will study controllability properties to infinite dimensional systems modeled by partial differential equations. We will extend the theory to the case of parabolic systems or hyperbolic systems with a particular attention to fluid systems. We also want to investigate the controllability of systems mixing hyperbolic and parabolic equations such as fluid-elastic interaction systems. We want in particular to develop new tools to handle coupled systems, where the coupling can appear as in a transmission problem. On the other hand, we will consider inverse problems for stationary, parabolic systems or hyperbolic systems with again a particular attention to fluid systems. We also want to tackle coupled/transmission systems such as fluid-structure interaction systems or cardiac models.

SCIPinPDEs

Title: Stabilization, Control and Inverse Problems in PDEs

Program: MATH-AmSud

Duration: January 1, 2023 – December 31st, 2026

Local supervisor: Takéo Takahashi

Partners:

- Brazil (Federal University of Paraiba)
- Chile (Universidad Tecnica Federico Santa Maria)

Inria contact: Takeo Takahashi

Summary: The objectives of this project are divided into three parts depending on the type of partial differential equations we want to control or stabilize. The first part is devoted to the study of control properties of some parabolic systems, appearing, for example, in cardiovascular models but also for other parabolic equations with various constraints. In a second part, we propose controllability problems for systems of hyperbolic type such as elasticity, wave or plate equations. The last part concerns systems mixing hyperbolic and parabolic equations such as fluid-elastic interaction systems or equations with memory.

9.1.3 Visits to international teams

Research stays abroad

- From December 4th to 18th, Julie Valein visited Axel Osses and Alberto Mercado at University of Chile and Universidad Federico Santa Maria.
- From November 11th to December 1st, Ludovick Gagnon visited Felipe Chaves and Stefanella Boatto at Universidad Federal da Paraiba and Universidad Federal do Rio de Janeiro. He also visited from December 6th to 15th, José Urquiza at Université Laval and Damien Van Pham Bang at Institut National de Recherche Scientifique

9.2 National initiatives

- ANR TRECOS, for New Trends in Control and Stabilization: Constraints and non-local terms, coordinated by Sylvain Ervedoza, University of Bordeaux. The ANR started in 2021 and runs up to 2024. TRECOS' focus is on control theory for partial differential equations, and in particular models from ecology and biology. SPHINX members : Ludovick Gagnon, Takéo Takahashi, Julie Valein
- ANR ODISSE, for Observer Design for Infinite-dimensional Systems, coordinated by Vincent Andrieu, University of Lyon. The ANR ends in 2023 and addresses theoretical aspects of observability and identifiability. SPHINX members : Ludovick Gagnon, Karim Ramdani, Julie Valein and Jean-Claude Vivalda

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

Member of the organizing committees

- Julien Lequeurre and Alexandre Munnier are co-organizers of the annual Workshop "Journées EDP de l'IECL".
- Julien Lequeurre is the co-organizers of the PDE seminar, in Metz, of the IECl.
- Julie Valein and Ludovick Gagnon were co-organizers of the PDE seminar, in Nancy, of the IECl.
- Rémi Buffe is the organizer of the groupe de travail d'EDP, in Nancy, of the IECL.
- Ludovick Gagnon was member of the organizing committee for the "control of dynamical systems" session of the 2022 Winter Meeting of the Canadian Mathematical Society.

10.1.2 Journal

Reviewer - reviewing activities

- SPHINX members were reviewers of several scientific journals in control theory and PDEs.

10.1.3 Invited talks

- Julie Valein was invited to give a talk in the " CA18232: Mathematical models for interacting dynamics on networks" for the European women in mathematics conference. She was also invited to give a seminar at Université de Lille and Université de Valenciennes.
- Ludovick Gagnon was invited to give a seminar at Université de Bordeaux, Universidad Federal do Rio de Janeiro and at Université Laval. He also gave a presentation at the TRECOS meeting in Marseille.

10.1.4 Leadership within the scientific community

- David Dos Santos Ferreira was one of the two coordinators of the GDR "Analyse des EDP" (until the end of 2022).

10.1.5 Research administration

- Since June 2021, Karim Ramdani is the head of the PDE team of IECL laboratory (the Mathematics laboratory of Université de Lorraine).
- Julie Valein is an elected member of the scientific pole AM2I of Université de Lorraine since 2022.

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.

10.2.2 Supervision

- Karim Ramdani and Alexandre Munnier are involved in the Ph.D supervision of Anthony Gerber Roth
- Takéo Takahashi is involved in the co-supervision, with Jérôme Lohéac (CRAN, Université de Lorraine), of Blaise Colle
- Takéo Takahashi is involved in the co-supervision, with Luz de Teresa (Uiversidad Nacional Autónoma de México), of Ying Wang
- Christophe Zhang is involved in the co-supervision, with Sébastien Martin (Université Paris Cité), Yannick Privat (Université de Strasbourg) and Camille Pouchol (Université Paris Cité), of Ivan Hasenohr
- SPHINX members are involved in the supervision of bachelor or master degree students projects.

10.2.3 Juries

- Julie Valein was member of the Ph.D jury of Xinyong Wang (Lille), Arthur Bottois (Clermont-Ferrand) and Amadou Cisse (Longwy)

10.3 Popularization

10.3.1 Internal or external Inria responsibilities

- Ludovick Gagnon is the international deputy of Inria Nancy – Grand Est. He is also involved in the integration of the new researchers of the center.
- Karim Ramdani is 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.

10.3.2 Interventions

Karim Ramdani gave several talks to review the most recent changes in scientific publishing, especially concerning the emergence of the dangerous author-pays model of open science.

11 Scientific production

11.1 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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11.2 Publications of the year

International journals

[11] X. Antoine and T. Khajah. 'NURBS-based Isogeometric analysis of standard and phase reduction On-Surface Radiation Condition formulations for acoustic scattering'. In: *Computer Methods in Applied Mechanics and Engineering* 392 (2022), p. 114700. URL: https://hal.science/hal-03167068.

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[13] X. Antoine and E. Lorin. 'Double-Preconditioning Techniques for Fractional Partial Differential Equation Solvers'. In: *Multiscale Science and Engineering* 4 (2022), pp. 137–160. URL: https://hal.science/hal-02340820.

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Reports & preprints

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11.3 Other

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