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Team CORIDA

Robust Control Of Infinite Dimensional Systems and Applications

Lorraine

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2. Overall Objectives

2.1. Overall Objectives

CORIDA is a team labeled by INRIA, by CNRS and by University Henri Poincaré, via the Institut Élie Cartan of Nancy (UMR 7502 CNRS-INRIA-UHP-INPL-University of Nancy 2). The main focus of our research is the robust control of systems governed by partial differential equations (called PDE's in the sequel). A special attention is devoted to systems with a hybrid dynamics such as the fluid-structure interactions. The equations modeling these systems couple either partial differential equations of different types or finite dimensional systems and infinite dimensional systems. We mainly consider inputs acting on the boundary or which are localized in a subset of the domain.

Infinite dimensional systems theory is motivated by the fact that a large number of mathematical models in applied sciences are given by evolution partial differential equations. Typical examples are the transport, heat or wave equations, which are used as mathematical models in a large number of problems in physics, chemistry, biology or finance. In all these cases the corresponding state space is infinite dimensional. The understanding of these systems from the point of view of control theory is an important scientific issue which has received a considerable attention during the last decades. Let us mention here that a basic question like the study of the controllability of infinite dimensional linear systems requires sophisticated techniques such as non harmonic analysis (cf. Russsell [67]), multiplier methods (cf. Lions [63]) or micro-local analysis techniques (cf. Bardos-Lebeau-Rauch [48]). Like in the case of finite dimensional systems, the study of controllability should be only the starting point of the study of important and more practical issues like feedback optimal control or robust control. It turns out that most of these questions are open in the case of infinite dimensional systems. Consequently, our aim is to develop tools for the robust control of infinite dimensional systems. More precisely, given an infinite dimensional system one should be able to answer two basic questions:

1. Study the existence of a feedback operator with robustness properties.
2. Find an algorithm allowing the approximate computation of this feedback operator.

The answer to question 1 above requires the study of infinite dimensional Riccati operators and it is a difficult theoretical question. The answer to question 2 depends on the sense of the word "approximate". In our meaning "approximate" means "convergence", i.e., that we look approximate feedback operators converging to the exact one when the discretization step tends to zero. From the practical point of view this means that our control laws should give good results if we use a large number of state variables. This fact is no longer a practical limitation of such an approach, at least in some important applications where powerful computers are now available. We intend to develop a methodology applicable to a large class of applications. Let us mention here only two of them.

1. **Acoustics and aero-acoustics.** We consider two types of applications :
   - Noise reduction by using active control (in a bounded region such as a plane cockpit) or by using absorbing materials (in open regions around highways, airports or railways).
   - Times reversal techniques for acoustic focusing in medical imaging, non destructive testing or sub-marine communication.
2. **The control of VLT's (Very Large Telescopes).** The operation of the current telescopes is based on the reception of infra-red waves. The reception is inevitably disturbed by the atmosphere, from where a correction of the wavefront is needed. Currently this correction is carried out by a mirror, whose diameter is approximately 20 cm, provided by a thousand of piezoelectric actuators. The future telescopes will be characterized by diameters much larger and the fact that the spectrum of the analyzed wavefront lies in the visible field. It is estimated that to correct the image with the same quality, the density of the actuators will have to be a hundred higher and that it will be necessary to replace the piezoelectric actuators by actuators resulting from micro-technology. It is thus a question of developing tools to model and to control the mirrors, allowing this change of scale.

3. Scientific Foundations

3.1. Analysis and control of fluids and of fluid-structure interactions

Keywords: *Korteweg de Vries equations*, *Navier-Stokes equations*, *analysis and control of fluids and fluid-structure interactions*, *motion of solids in viscous fluids*.

The problems we consider are modeled by the Navier-Stokes, Euler or Korteweg de Vries equations (for the fluid) coupled to the equations governing the motion of the solids. One of the main difficulties of this problem comes from the fact that the domain occupied by the fluid is one of the unknowns of the problem. We have thus to tackle a *free boundary problem*.

The control of fluid flows is a major challenge in many applications: aeronautics, pollution issues, regulation of irrigation channels or of the flow in pipelines, etc. All these problems cannot be easily reduced to finite dimensional models so a methodology of analysis and control based on PDE's is an essential issue. In a first approximation the motion of fluid and of the solids can be decoupled. The most used models for an incompressible fluid are given by the Navier-Stokes or by the Euler equations.

The optimal open loop control approach of these models has been developed from both the theoretical and numerical points of view. Controllability issues for the equations modeling the fluid motion are by now well understood (see, for instance, [59] and the references therein). The feedback control of fluid motion has also been recently investigated by several research teams (see, for instance [47] and references therein) but this field still contains an important number of open problems (in particular those concerning observers and implementation issues). One of our aims is to develop efficient tools for computing feedback laws for the control of fluid systems.

In real applications the fluid is often surrounded by or it surrounds an elastic structure. In the above situation one has to study fluid-structure interactions. This subject has been intensively studied during the last years, in particular for its applications in noise reduction problems, in lubrication issues or in aeronautics. In this type of problems, a PDE's system modeling the fluid in a cavity (Laplace equation, wave equation, Stokes, Navier-Stokes or Euler systems) is coupled to the equations modeling the motion of a part of the boundary. The difficulties of this problem are due to several reasons such as the strong nonlinear coupling and the existence of a free boundary. This partially explains the fact that applied mathematicians have only recently tackled these problems from either the numerical or theoretical point of view. One of the main results obtained in our project concerns the global existence of solutions in the case of a two-dimensional Navier-Stokes fluid (see [5]).

The numerical methods used for computing the solutions of fluid or fluid structure problems in a direct setting (i.e., with given inputs) considerably progressed during the last years. For the corresponding control problems the literature contains only a small number of effective methods. Our first results in this direction concern a model arising in hydraulics (the linearized Saint-Venant equations).

Another topic of great interest is the control of the interface of two fluids (typically water and air) by using as input the velocity of a moving wall which is a part of the boundary. One of the most popular models for this problem is given by the shallow water equations (Saint Venant equations) which neglect the dispersive effects. The controllability of several important systems governed by this type of equations has received a considerable attention during the last decade. Let us mention here the important work by Coron [53]. If dispersive effects are considered the relevant model is given by the Korteweg de Vries equation. The first work on the control of this equation goes back to Russell and Zhang (see [68]). An important advance in the study of this problem has been achieved in the work [4] where, for the first time, the influence of the length of the channel has been precisely investigated.

3.2. Frequency domain methods for the analysis and control of systems governed by pde's

Keywords: *Helmholtz equation*, *control and stabilization*, *numerical approximation of LQR problems*, *time-reversal*.

We use frequency tools to analyze different types of problems. The first one concerns the control, the optimal control and the stabilization of systems governed by PDE's, and their numerical approximations. The second one concerns time-reversal phenomena, while the last one deals with the numerical approximation of the Helmholtz equation using domain decompositions techniques.

3.2.1. Control and stabilization for skew-adjoint systems

The first area concerns theoretical and numerical aspects in the control of a class of PDE's. More precisely, in a semigroup setting, the systems we consider have a skew-adjoint generator. Classical examples are the wave, the Bernoulli-Euler or the Schrödinger equations. Our approach is based on an original characterization of exact controllability of second order conservative systems proposed by K. Liu [64]. This characterization can be related to the Hautus criterion in the theory of finite dimensional systems (cf. [57]). It provides for time-dependent problems exact controllability criteria **that do not depend on time, but depend on the frequency variable** conjugated to time. Studying the controllability of a given system amounts then to establishing uniform (with respect to frequency) estimates. In other words, the problem of exact controllability for the wave equation, for instance, comes down to a high-frequency analysis for the Helmholtz operator. This frequency approach has been proposed first by K. Liu for bounded control operators (corresponding to internal control problems), and has been recently extended to the case of unbounded control operators (and thus including boundary control problems) by L. Miller [66]. Let us emphasize here that one further important advantage of this frequency approach lies in the fact that it can also be used for the analysis of space semi-discretized control problems (by finite element or finite differences). The estimates to be proved must then be uniform with respect to **both the frequency and the mesh size**.

3.2.2. Time-reversal

The second area in which we make use of frequency tools is the analysis of time-reversal for harmonic acoustic waves. This phenomenon [55] is a direct consequence of the reversibility of the wave equation in a non dissipative medium. It can be used to **focus an acoustic wave** on a target through a complex and/or unknown medium. To achieve this, the procedure followed is quite simple. First, time-reversal mirrors are used to generate an incident wave that propagates through the medium. Then, the mirrors measure the acoustic field diffracted by the targets, time-reverse it and back-propagate it in the medium. Iterating the scheme, we observe that the incident wave emitted by the mirrors focuses on the scatterers. An alternative and more original focusing technique is based on the so-called D.O.R.T. method [56]. According to this experimental method, the eigenelements of the time-reversal operator contain important information on the propagation medium and on the scatterers contained in it. More precisely, the number of nonzero eigenvalues is exactly the number of scatterers, while each eigenvector corresponds to an incident wave that selectively focuses on each scatterer.

Time-reversal has many applications covering a wide range of fields, among which we can cite **medicine** (kidney stones destruction or medical imaging), **sub-marine communication** and **non destructive testing**. Let us emphasize that in the case of time-harmonic acoustic waves, time-reversal is equivalent to phase conjugation and involves the Helmholtz operator.

3.2.3. Numerical approximation of high-frequency scattering problems

This subject mainly deals with the numerical solution of the Helmholtz or Maxwell equations for open region scattering problems. This kind of situation can be met e.g. in radar systems in electromagnetism or in acoustics for the detection of underwater objects like submarines.

Two particular difficulties are considered in this situation

- the wavelength of the incident signal is small compared to the characteristic size of the scatterer,
- the problem is set in an unbounded domain.

These two problematics limit the application range of most common numerical techniques. The aim of this part is to develop new numerical simulation techniques based on microlocal analysis for modeling the propagation of rays. The importance of microlocal techniques in this situation is that it makes possible a local analysis both in the spatial and frequency domain. Therefore, it can be seen as a kind of asymptotic theory of rays which can be combined with numerical approximation techniques like boundary element methods. The resulting method is called the On-Surface Radiation Condition method.

3.3. Optimal location of sensors and of actuators

Keywords: *decay rate*, *robustness*.

We focus here on algorithms for optimizing the location and the shape of actuators and of sensors for the stabilization of systems governed by PDE's.

Let us consider a control problem for a system governed by PDE's with the input acting at the interior of the domain or on a part of the boundary. An important question is to find the location and the form of the control region in order to optimize a criterion imposed by the user. This criterion should take in consideration the energy decay rate and the robustness properties. A priori the topology of the control region is unknown so the first step in such a study should be the application of topological optimization techniques. An important particular case is the case when the actuators and sensors contain smart materials. Generally, the optimal location problems are far from the classical convex optimization problems and they don't have a unique global optimum. To our knowledge, the only problem where the explicit solution is known has been studied in Ammari, Henrot and Tucsnak [44]. This is why finding numerical methods to be used in order to approach the optimum location is a hard task.

3.4. Well–posed linear systems and weak coupling

Keywords: *boundary control*, *coupling mechanism*, *linear evolution equations*, *stabilization*.

We consider well–posed systems coupling two types PDE's or coupling PDE's and ordinary differential equations. The methods we use combine energy estimates, multipliers techniques and spectral analysis.

Well–posed linear systems form an important class of infinite dimensional systems which has been introduced by Salamon in [69]. Roughly speaking a *well–posed linear system* is a linear time-invariant system such that on any finite time interval, the operator from the initial state and the input function to the final state and the output function is bounded. An important subclass of well–posed linear systems is formed by the *conservative systems* which satisfy an energy-balance equation. More precisely, in a conservative system, the energy stored in the system at time τ plus the outgoing power equals the sum of the initial energy stored in the system and of the incoming power. It turns out that a large number of systems governed by partial differential equations are of this type. Moreover, conservative systems have remarkable properties like the fact that their exact controllability is equivalent to their stability. Therefore a systematic functional analytic approach to this system seems important for the infinite dimensional systems community.

We are in particular interested in problems in which two types of PDE's interact such as: a plate equation and a wave equation, a wave or plate type equation coupled to ordinary differential equations, or two wave equations coupled by lower order terms. This type of system is sometimes designed as a "hybrid system" (notice that this term is often used for a different notion in control theory). The main difficulty of these problems is that the inputs act in only one of the equations of the system. In this case we say that we have a *weak coupling*. The basic question is to know if such a system is stabilizable. A general framework for this type of problem has been given in Alabau [2] and [1] where the use of multipliers method yields promising results. A different way to tackle the same problem is to first study the simultaneous controllability of the uncoupled systems. The case in which one of the systems is finite dimensional has been tackled in Tucsnak and Weiss [6].

3.5. Implementation

Keywords: *Dicretization*, *Riccati equation*.

This is a transverse research axis since all the research directions presented above have to be validated by giving control algorithms which are aimed to be implemented in real control systems. We stress below some of the main points which are common (from the implementation point of view) to the application of the different methods described in the previous sections.

For many infinite dimensional systems the use of co-located actuators and sensors and of simple proportional feed-back laws gives satisfying results. However, for a large class of systems of interest it is not clear that these feedbacks are efficient, or the use of co-located actuators and sensors is not possible. This is why a more general approach for the design of the feedbacks has to be considered. Among the techniques in finite dimensional systems theory those based on the solutions of infinite dimensional Riccati equation seem the most appropriate for a generalization to infinite dimensional systems. The classical approach is to approximate an LQR problem for a given infinite dimensional system by finite dimensional LQR problems. As it has been already pointed out in the literature this approach should be carefully analyzed since, even for some very simple examples, the sequence of feedbacks operators solving the finite dimensional LQR is not convergent. Roughly speaking this means that by refining the mesh we obtain a closed loop system which is not exponentially stable (even if the corresponding infinite dimensional system is theoretically stabilized). In order to overcome this difficulty, several methods have been proposed in the literature : filtering of high frequencies, multigrid methods or the introduction of a numerical viscosity term. We intend to first apply the numerical viscosity method introduced in [72], for optimal and robust control problems.

4. Application Domains

4.1. Panorama

Keywords: *acoustics*, *aero-acoustics*, *control of VLT's (Very Large Telescopes)*.

As we already stressed in the previous sections the robust control of infinite dimensional systems is an emerging theory. Our aim is to develop tools applicable to a large class of problems which will be tested on models of increasing complexity. We describe below only the applications in which the members of our team have recently obtained important achievements.

4.2. Acoustics

Keywords: *Helmholtz equation*, *Noise reduction*.

One of the application domains of our work concerns the reduction of the noise due to the plane's engines during the take-off. This problem is addressed in the framework of the PhD thesis of Stefan Duprey at the Research Center of EADS (CIFRE contract). Antoine Henrot was his advisor, but his work was also supervised in Nancy by Karim Ramdani. In EADS, at Suresnes, his work was supervised by Isabelle Terrasse and François Dubois.

The main steps of this study of noise reduction are the following :

1. We write a code to compute the flow. Starting from the Euler equations in the potential and isentropic case, we are lead to solve a well–known non-linear elliptic problem, studied for example, in classical books like Glowinski or Nečas. To solve numerically this non linear problem, we use a fixed-point algorithm which turns out to be convergent.
2. We assume the acoustic perturbation to be potential and decoupled from the flow. By linearization of Euler equations, we get a linear problem satisfied by the acoustic potential. The coefficients of this equation involve the potential flow computed at step 1. The boundary conditions are either of Neumann or impedance type.
3. We have to write a code to compute the solution of step 2. The fact that the flow can be considered constant at infinity simplifies the equation outside a large domain containing the plane. This leads to two possible ways to solve this problem: using globally a Lorentz transform or using a domain decomposition method.
4. When the two previous codes work satisfactory, we can imagine optimization procedures by acting either on the shape of the engine or on its coating.

During his thesis (defended in October 2006), Stefan Duprey realized efficiently points 1 to 3. Moreover, he was also able to handle the theoretical questions of existence and uniqueness of a solution. At least three papers should follow from the whole work.

4.3. Control of VLT's (Very Large Telescopes)

Keywords: *adaptive optics*, *robust control*, *turbulence*, *wavefront*.

The objective of this work is to use the tools of infinite-dimensional system automatics for the control of large telescopes.

The future telescopes will be characterized by diameters much larger than the current ones and the fact that the spectrum of the analyzed wavefront lies in the visible field. It is estimated that to correct the image with the same quality, the density of the actuators will have to be multiplied by one hundred and that it will be necessary to replace the piezoelectric actuators by actuators resulting from micro-technology. In theory, a telescope provided with actuators and sensors can be modeled like a finite-dimensional system. When the number of sensors and actuators becomes very large, it is often difficult to use this type of modeling to control the telescope.

Our prime objective is to obtain, by techniques of asymptotic analysis, models based on systems of partial differential equations, with distributed control. According to the structure of the obtained system we suggest to apply modern techniques resulting from the theory of the control of **infinite**-dimensional systems. The input and the output of the system will remain of finite dimensions, which will allow the direct application of the results to the initial system. The obtained systems will couple equations modeling the structure and the equations modeling the sensors and the actuators (for example equations of electrostatics). One of the difficulties of the problem lies in the fact that control occurs only in one of the equations of the system. A detailed attention will be given to the problems of optimal positioning of the control fields. It is the question of finding the localization and the form to be given to the actuators and the sensors so that the control is as effective as possible.

In a first approximation, which is valid for infra-red waves, we use the geometrical optics to study the system. In this case, by linearizing the equations, we have justified some of the approximations used in engineers literature. Currently, we work directly on the nonlinear equations obtained with the geometrical optics approach, and we look for an approximation valid when the spectrum of the analyzed wavefront lies in the visible field.

4.4. Automotive industry

We applied some modern techniques of automatic control to the command of the cooling of the fuel cells stack; these techniques result in a significant enhancement of the functioning of the cooling circuit. This problem is studied in the framework of the PhD thesis of Fehd Ben Aïcha (co-supervised with M. Sorine, head of the SOSSO2 project).

4.5. Switched reluctance motor

High-speed Machining experienced a considerable development these last years. Under the impulse of a keen demand of the aircraft industry, high-speed machining centers have been developed to manufacture parts of high degree of accuracy out of aluminium, titanium, and their alloys. The mechanical engineering industry then largely attempted to develop the high-speed machining for the manufacture of more conventional parts. In collaboration with the LGIPM (Laboratoire de Génie Industriel et Production Mécanique), the issue of the modeling and the automatic control of switched reluctance motor has been the subject of a thesis [8].

5. Software

5.1. SCISPT Scilab toolbox

Keywords: *Scilab*, *sparse matrices*.

Participant: Bruno Pinçon [correspondant].

Our aim is to develop Scilab tools for the numerical approximation of PDE's. This task requires powerful sparse matrix primitives, which are not currently available in Scilab. We have thus developed the SCISPT Scilab toolbox, which interfaces the sparse solvers UMFPACK v4.3 of Tim Davis and TAUCS SNMF of Sivan Toledo. It also provides various utilities to deal with sparse matrices (estimate of the condition number, sparse pattern visualization, etc.). We intend to extend this work in the framework of collaborations with the Scilab consortium recently created.

6. New Results

6.1. Analysis and control of fluids and of fluid-structure interactions

Keywords: *Korteweg de Vries equations*, *Navier-Stokes equations*.

Participants: Séverine Baillet, Thomas Chambrion, Antoine Henrot, Jean Houot, Alexandre Munnier, Lionel Rosier, Jean-François Scheid, Mario Sigalotti, Takéo Takahashi, Jean-Baptiste Tavernier, Marius Tucsnak, Jean-Claude Vivalda.

A part of our activity in this field has been devoted to the study of well–posedness and to the numerical analysis of the equations modeling the motion of rigid bodies in an incompressible fluid. An important part of this work is done in collaboration with a group from the University of Chile through the associated team ANCIF. Many of the works we are quoting in what follows have been done with a member of this group (Jorge San Martín, Jaime Ortega, Carlos Conca, Patricio Cumsille).

Concerning the well–posedness results, the last main achievements are reported in the papers [24], [19]. In reference [71] we gave an existence and uniqueness result in the case of a viscous fluid filling the exterior of an infinite cylinder. The generalization of this result to more general geometries is studied in reference [19]. In this recent work of Cumsille and Tucsnak, the well–posedness of Navier-Stokes flow in the exterior of a rotating obstacle has been proved. Recently Cumsille and Takahashi have obtained the well–posedness in the case of a rigid body of arbitrary shape moving in a viscous incompressible fluid. In the paper [15], the authors prove the global in time existence of a *classical* solution for the equations modeling the motion of a rigid body of arbitrary shape moving in a perfect incompressible fluid. The regularity of the solutions is an important issue, as most of the control results for Euler systems are based of Coron's return method and so they involve smooth solutions. Notice also that a similar result for Navier-Stokes system is not yet available.

In the last year, we have started to study the motion of aquatic organisms. More precisely, in [31], Takahashi and Tucsnak have considered the control of the motion of the rigid bodies moving in a fluid by using a velocity or a torque control acting on the rigid part only. They have obtained several reachability results at low Reynolds number. These results give a new insight of the very interesting propulsion mechanisms used by ocean micro-organisms (like ciliata). In [30], Scheid, Takahashi and Tucsnak have given and analyzed a model for the motion of a fish. The model consists in a solid undergoing an undulatory deformation, which is immersed in a viscous incompressible fluid. The displacement of the "creature" is decomposed into a rigid part and a deformation (undulatory) part. One of the particularities of the work is that no particular constitutive law for the solid are used but instead the non–rigid part of the deformation is imposed. The advantages of this approach consist in the global character (up to possible contacts) of the obtained strong solutions and in the possibility of using numerical methods inspired by those developed in the rigid-fluid case. In fact, by considering a similar method to the one developed in the article [70], numerical simulations have been performed for the motion of a fish into a viscous incompressible fluid. Recall that the non-rigid part of the deformation is only imposed and the trajectory of the fish is not prescribed. We numerically observe that the fish manages to go ahead and thus a self-propelled motion is reached by the fish. A numerical code has been developed for the 2D case in Scilab with the use of the SCISPT toolbox for sparse solver (see Section 5).

Since September 2006, an INRIA associated engineer has been recruited to improve the current numerical code, to rewrite it in the Matlab software and finally to develop a 3D software for the fish-like swimming. The improvement of the 2D code is in progress and deals with the Navier-Stokes solver together with the optimization of the Matlab implementation of the numerical code. The Navier-Stokes solver has to allow to tackle realistic situations where the Reynolds number lies between 10^3 and 10^6, depending on the nature of the fish-like swimming we consider (trout, salmon, eel, ...). The development of the 3D software is not started yet.

Another control problem has been obtained by Takahashi (in collaboration with Imanuvilov) for a fluid–structure system ([21]). More precisely, it is proved that we can control (locally) the motion of both the rigid bodies and of the fluid by using an input given by the velocity field of the fluid on a part of the exterior boundary of the domain. This question has a more theoretical motivation: we want to show that the presence of the rigid bodies does not change in an essential way the controllability properties of the system.

The same problem may be tackled with a perfect fluid (not necessarily potential), the normal component of the fluid velocity being controlled on a small part of the boundary. For a ball in 2D, it has been shown by Rosier that we may control the position of the ball, the ball being at rest at the beginning and at the end of the control process. The extension to a solid with one axial symmetry (boat) is under investigation with O. Glass (Paris 6).

Another situation which has been treated is the one of a rigid body moving in an inviscid fluid. More precisely, T. Chambrion and M. Sigalotti studied the controllability properties of an ellipsoidal neutrally buoyant underwater vehicle immersed in an infinite volume of an inviscid incompressible fluid in irrotational motion. (See [51] and [33].) Due to the potential nature of the flow, the state of the system is fully determined by a finite set of real variables which parameterize the set of configurations (position and attitude) of the moving body and its linear and angular momenta. The dynamics of such momenta, seen from the perspective of the solid, are described by the classical Kirchhoff equations whose control properties have been thoroughly studied (see for instance [62], [45]). In [51] and [33] we tackle the less studied problem of controlling and stabilizing the full 12-dimensional nonlinear system describing the evolution of configuration and momenta.

The Korteweg-de Vries (kDV) equation is a popular model for the propagation of small-amplitude long water waves in a uniform channel. In a series of papers, Russell and Zhang have proved in the 90s that we may *locally* stabilize the KdV equation by means of a internal control supported in a small interval. Some significant improvement have been recently obtained by L. Rosier and B-Y Zhang. The paper [29] is concerned with the internal stabilization of the generalized Korteweg-de Vries equation on a bounded domain. The global well–posedness and the exponential stability are investigated when the exponent in the nonlinear term ranges over the interval $[1, 4)$. The global exponential stability is obtained whatever the location where the damping is active, confirming positively a conjecture of Perla Menzala, Vasconcellos and Zuazua.

Another quite different problem in fluid-structure interaction comes from the industrial PhD thesis of Baillet. At the end of the exploitation of an oil well, surface pumps are no longer efficient enough to extract the oil remaining in the reservoir. Instead of closing the well, oil companies might use well–pumps, introduced deep into the ground in order to maintain the production. Such pumps are composed of a succession of identical stages (typically 15–20 stages, but it could go up to 100 stages) arranged in series. The process optimization needs numerical simulation, but representing the whole pump numerically is impossible (for obvious calculation costs). Thus it is necessary to simplify the model, by representing only one stage. Therefore, a very natural question which arises is the following: does the flow in one standard stage of the pump looks like the one we would obtain by considering periodic boundary conditions at the entrance and exit of the stage. Of course, one cannot hope that this kind of result holds for the first and the last stages which are still influenced by the boundary conditions at the top and the bottom of the pump. Baillet, Henrot and Takahashi have obtained in [16] an exponential convergence with respect to the number of stages when the fluid motion is modeled by the Stokes equations.

6.2. Frequency tools for the analysis of pde's

Participants: Bruno Pinçon, Karim Ramdani, Lionel Rosier, Takéo Takahashi, Marius Tucsnak.

6.2.1. Control and stabilization of systems governed by pde's and their numerical approximation

It is well–known that the solution of LQR optimal control problems is given through a feedback operator involving a Riccati operator P. This operator solves a Riccati equation in infinite dimension. Of course, in practice, one can only determine an approximate solution P_h of this equation, and the natural question that arises is the following : does the approximate solution obtained using this operator P_h (instead of P) converge to the solution of the continuous problem? This question has been so far studied by many authors (see for instance [40], [60], [46]). In all these papers, one of the main assumptions is that the discretized systems should be **uniformly stabilizable** with respect to the discretization parameter h. Unfortunately, most of the standard numerical methods (finite element or finite differences) do not fulfill this condition. Using the frequency characterization of stabilizability proposed by Liu and Zheng in [65], we have given in [26] a general technique ensuring the uniform stabilizability of classical numerical methods (finite element or finite differences). This technique consists in adding to the standard numerical schemes a suitable numerical viscosity. Compared to the results of [72], the main novelties brought in by our results lie in their generality, since they hold for the finite element space semi-discretization of a wide class of second order evolution equations.

In [27], we study the internal stabilization of the Bernoulli-Euler plate equation in a square. The continuous and the space semi-discretizated problems are successively considered and analyzed using a frequency domain approach. For the infinite dimensional problem, we provide a new proof of the exponential stability result, based on a two dimensional Ingham's type result. In the second and main part of the paper, we propose a finite difference space semi-discretization scheme and we prove that this scheme yields a uniform exponential decay rate (with respect to the mesh size).

In [39] we study the boundary controllability properties of a wave equation with structural damping $y_{tt} - y_{xx} - \epsilon y_{txx} = 0$, $y(0,t) = 0$, $y(1,t) = h(t)$ where ϵ is a strictly positive parameter depending on the damping strength. We prove that this equation is not spectrally controllable and that the approximate controllability depends on the functional space in which the initial value Cauchy problem is studied.
In [37] we consider a Bernoulli-Euler beam, which is clamped at one boundary and free at the other, and to which are attached a piezoelectric actuator and a collocated sensor. We provide an output feedback law and characterize the sensor/actuator location for which the strong stabilization holds. In [22] we focus on the important case when the actuator/sensor is touching the clamped extremity of the beam. We prove then that the energy decreases to zero in a polynomial way for almost all lengths, and in an exponential way for lengths admitting a certain coprime factorization.

6.2.2. Acoustics

In [50], we study two mathematical time-harmonic near field models for time reversal in a homogeneous and non-dissipative medium containing sound-hard obstacles. The first one takes into account the interactions between the mirror and the obstacles. The second one provides an approximation of these interactions. We prove, in both cases, that the time reversal operator T is self-adjoint and compact. The D.O.R.T method (French acronym for Decomposition of the Time Reversal Operator) is explored numerically. In particular, we show that selective focusing, which is known to occur for small and distant enough scatterers, holds when the wavelength and the size of these scatterers are of the same order of magnitude (medium frequency situation). Moreover, we present the behavior of the eigenvalues of T according to the frequency and we show their oscillations due to the interactions between the mirror and the obstacles and between the obstacles themselves.

In [25], we investigate the acoustic selective focusing properties of time reversal in a two-dimensional acoustic waveguide. A far-field model of the problem is proposed in the time-harmonic case. In order to tackle the question of selective focusing, we derive an asymptotic model for small scatterers. We show that in the framework of this limit problem, approximate eigenvectors of the time reversal operator can be obtained when the number of propagating modes of the waveguide is large enough. This result provides in particular a mathematical justification of the selective focusing properties observed experimentally. Some numerical experiments of selective focusing are also presented.

6.2.3. Numerical methods for high-frequency scattering problems using microlocal analysis

In [15], a new On-Surface Radiation Condition is introduced. The construction takes care of the different kinds of contributions which compose the scattered ray. Mathematically, the condition is given through a square-root operator. A paraxialization process of this operator based on Padé approximants in combination with an iterative finite element scheme leads to an efficient and accurate numerical method. A complete review of the On-Surface Radiation Condition method is provided in the Chapter Book [13]. In a collaboration with Y. Boubendir from the University of Minneapolis, the development of integral operator based preconditioners for solving the scattering problem by a penetrable body is presented in [14].

6.3. Optimal location of sensors and of actuators

Participant: Antoine Henrot.

This topic was the subject of the thesis of Pascal Hébrard who left our team at the end of 2002. He is currently working as a research engineer at Dassault Systems. Nevertheless, we kept in touch during this year since we wanted to understand and write precisely the "spillover phenomenon" that we pointed out last year. Let us explain what it is. When we want to damp a vibrating body, we have in principle to act on all the eigenfrequencies of the body. In practice, it is common to consider that high frequencies are not so penalizing and that we can only take into account the low frequencies. Therefore, we decided to simplify the criterion we introduced in [3] and which involves all the eigenmodes (this criterion corresponds to some rate of decay of the total energy of the system), by introducing a new criterion, say J_N involving only the N first eigenmodes of the damped system. Then, we are led to look for an internal domain which damps those N modes as good as possible, i.e. a domain which maximizes our criterion J_N. We were able to prove, in one dimension (that is to say for a damped string) that:

- There exists a unique solution ω_N^* to the previous minimization problem. This set ω_N^* represents the optimal location of actuators when we want to damp only the N first modes.
- The set ω_N^* is composed of at most N connected components.
- When the length constraint l goes to zero (i.e. we consider a small zone of control), the set ω_N^* concentrates on the nodes of the $(N+1)$-th mode. It means that it does not control it at all. In other terms, the best domain for the N-th first eigenmodes is the worst for the $(N+1)$-th eigenmode!

This work is published in [58]. We would now like to know if this phenomenon is related to the choice of our model (criterion and state equation) or if it is a more general situation. Moreover, we would like to extend this result to higher dimension. Even in two dimensions, for general domains, the formal proof seems much harder, in particular we need spectral properties which are not known in a general context.

With Steve Cox, we started to study another problem also related to the damping of eigenmodes in a string. It is a question relating to a model for harmonics on stringed instruments which could be set as: is it possible to achieve “Correct Touch” in the pointwise damping of a fixed string? By correct touch, we consider the following. When we place a finger lightly at one of the nodes of the low frequency harmonics, it forces the string to play a note that sounds like a superposition of those normal modes with nodes at the location of the finger. Now, the question is to determine what should be the pressure of the finger in order to best damps the remaining modes. From a mathematical point of view, we consider the wave equation with a damping as $b\delta_a u_t$ where u_t is the speed, a the location of the pressure, δ_a is the Dirac distribution at a and b the intensity of the pressure. We want to determine, for each a what is the b which minimizes the spectral abscissa of the modes not vanishing at a. This involves a precise qualitative analysis of the spectrum of the damped operator in the complex plane. This is still a work in progress, but we have already obtained significant results which are given in [54].

6.4. Well–posed linear systems and weak coupling

Participant: Fatiha Alabau.

Carleman estimates and null controllability for degenerate parabolic equations :

In [12], we prove a Carleman estimate for a one-dimensional adjoint heat equation which degenerates at the boundary of the spatial domain and apply this result to prove null controllability for the direct equation. Such models occur in diffusion processes (transition probabilities), as well as in population genetics and boundary layer models for fluids. We plan to study extensions to more general equations such as two-dimensional models, and other types of boundary conditions.

Stabilization for visco-elastic materials :

In the work under progress, we study visco-elastic materials for which the feedback law is of memory type, that is the feedback appears as a convolution operator with respect to time. We prove stabilization properties such as exponential or polynomial decay for general abstract hyperbolic equations with applications to various models. We plan to study more complex models, such as coupled mechanical systems.

Nonlinear dissipation effects without growth assumptions :

In [42], [43], we give a general semi-explicit formula which gives optimal decay estimates of the energy of solutions of general abstract second order hyperbolic equations, provided that a general estimate linking a weighted integral of the energy with respect to time in terms of the linear and nonlinear kinetic energies holds. We give applications to the wave equation with locally distributed and boundary nonlinear feedback laws. Optimality is proved for several one-dimensional nonlinear boundary dissipation cases. In [11], we apply these results to Petrowsky equations with locally distributed nonlinear feedbacks by extending the piecewise multiplier method. In [10], we show that this new method can be applied with success to coupled systems such as Timoshenko beams, subjected to first order coupled and a single control force. We prove general decay estimates (of polynomial, logarithmic ..., type) depending on the growth properties of the feedback at the origin in case of equal speeds of propagation for the equation of the transverse displacement of the beam and of the rotation angle. In case of different speeds of propagation, we prove polynomial decay for smooth solutions in case of globally Lipschitz nonlinear feedbacks, with linear growth.

Indirect stabilization and controllability

In [1], [2], we study general polynomial decay properties of the energy for weakly coupled hyperbolic systems subjected to a single feedback force applied directly to one equation, the other equation being indirectly stabilized. In [41], general indirect boundary observability results where obtained for the adjoint equation and exact indirect controllability results for the direct equation derived. These results states in particular that it is sufficient to observe, on a convenient part of the boundary, only a component of the unknown state vector, to derive full information on the initial energy of the full state vector. Extension to various coupled mechanical systems is under study with W. Youssef (doctoral student).

6.5. Miscellaneous

Participants: Jean-Pierre Croisille, Antoine Henrot, Lionel Rosier, Mario Sigalotti, Jean-Claude Vivalda.

In this section we briefly describe several important achievements obtained during the last year and which cannot be easily included in one of the themes above.

6.5.1. Jean-Pierre Croisille

In [49], a pure-streamfunction formulation is introduced for the numerical simulation of the two-dimensional incompressible Navier-Stokes equations. The idea is to replace the vorticity in the vorticity-streamfunction evolution equation by the Laplacian of the streamfunction. A compact numerical scheme and a number of numerical experiments are presented. In [17], the convergence analysis of the scheme for the full time-dependent Navier-Stokes equations is presented.

6.5.2. Antoine Henrot

In the book [7], Henrot focuses on extremal problems. For instance, he look for a domain which minimizes or maximizes a given eigenvalue of the Laplace operator with various boundary conditions and various geometric constraints. He also considers the case of functions of eigenvalues. He investigates similar questions for other elliptic operators, like Schrödinger operator, non homogeneous membranes, bi-Laplacian and he also looks at optimal composites and optimal insulation problems in terms of eigenvalues. This book shows old and new results on the subject with a self-contained presentation of classical isoperimetric inequalities for eigenvalues. It should be useful for pure and applied mathematicians more particularly interested in partial differential equations, calculus of variations, differential geometry, spectral theory, but also for other scientists who need properties of eigenvalues in their field of research.

6.5.3. Lionel Rosier

6.5.3.1. Synchronization of Chaos and Cryptography

In [28] a class of chaotic systems on the N-dimensional torus is investigated. It is proved that any dynamical system in this class is chaotic in the sense of Devaney, and that the sequences produced are equidistributed for almost all initial data. Such a class is of particular interest since it fulfills most of the requirements of efficient cryptographic schemes involving recursive algorithms. Then, a masking technique based on a dynamical embedding is proposed and a way of extracting the masked information is provided through a synchronization mechanism with global convergence property.

6.5.3.2. Adaptative Optics

In [61] we consider an adaptive optical system in which a deformable mirror is controlled to compensate for random wavefront disturbances. For most systems of this type, the shape of the mirror is taken as a linear function of the wavefront error, leading to satisfactory results in *linear* regimes. Here, the geometric shape of the mirror leading to a *perfect* correction of the wavefront is derived. Next, a control is designed to reach that geometric shape when the deformable mirror is a membrane mirror with electrostatic actuators. Numerical simulations illustrating the improvements supplied by the geometric approach are also reported here.

In [36] we consider a large bimorph mirror which is composed of three layers: a purely elastic layer, a layer equipped with a distribution of sensor piezoelectric inclusions, and a layer equipped with a distribution of actuator piezoelectric inclusions. Such a device is modeled by a system of two coupled PDE, the first one involving a second-order operator without time derivative, and the second one being a plate equation. The controllability properties are investigated for both the 1D model and the 2D model, and an output feedback law is proposed for the stabilization of the 1D model.

6.5.4. Mario Sigalotti

In [18] we prove some sufficient and some necessary conditions for the global asymptotic stability of nonlinear switching systems on the plane. The main advantage of such conditions is that they can be verified without any integration or construction of a Lyapunov function, and that they are robust with respect to small perturbations of the system.

[32] is the second part of a research project started in [52], whose goal is to address some questions about the controllability of systems modeling a Dubins-like car moving on non-flat surfaces. In particular, this second contribution studies the case where the Gaussian curvature of the surface is non-positive.

6.5.5. Jean-Claude Vivalda

6.5.5.1. Euler-Lagrange systems

We consider mechanical systems which are modelized through the Euler-Lagrange equations

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+V(q)=\tau \tag{1}$$

where only the positions q are measured but not the velocities. We characterize the systems for which a transformation of the form $(q,\dot{q}) \mapsto (\Theta(q), T(q)\dot{q})$, with $\frac{\partial\Theta}{\partial q} = T(q)$ and $\dot{T}(q) = T(q)M^{-1}(q)C(q,\dot{q})$, exists. The importance of such transformations lies in the fact that it transforms the above system in another system which is linear with respect to the unmeasured variables. In this way, issues like design of an observer or tracking trajectory become easy to solve. In a particular case we obtained a transformation which puts system (1) under a form which is triangular with respect to the velocities, again, this form allows us to design an observer and also to make output stabilization [38], [23].

6.5.5.2. Observability

We continued our work on the genericity of the observability by showing that, for discrete-time systems, the strong differential observability is generic provided that the number of outputs is greater than the number of inputs [9].

6.5.5.3. Switched reluctance motor

In the framework of the PhD thesis of Ismaïl Gourragui (co-financed by the Inria and the “Conseil régional de Lorraine”), we tackled some problems about the switched reluctance motor. First, we wanted to compute the losses due to the eddy currents and the losses due to the hysteresis. We implemented a method taking account this phenomena in a solver of PDE [34]. By using an elementary method of optimal control, we compute a command law for the optimization of the torque exerted by the motor [20]. We study three possible shapes for the rotor from the point of view of the performances of the machine [35] and we design an practical observer for the (finite dimensional) system describing the motion of the rotor, this observer gives an estimation of the position and the angular velocity of the rotor subject to an external torque regarded as an unknown input.

7. Contracts and Grants with Industry

7.1. Contracts and Grants with Industry

A CIFRE contract has been signed with IFP (French Center of Research and Industrial Development for oil and automotive industries, based in Rueil-Malmaison). Indeed, S. Baillet began a PhD program (advisor A. Henrot), funded by a CIFRE grant, in June 2004. The aim of this work consists in improving the efficiency of the pump sucking the crude oil from the subsoil. The control variable is the geometry of the pump and the output of the system is gap of pressure. The system is governed by the three-dimensional Navier-Stokes equations. Instead of computing the exact gradient of the criterion (which seems too difficult or too costly), we intend to compute an incomplete gradient, possibly coupled with *one-shot* type methods. Then, a classical gradient-type or Quasi-Newton optimization algorithm is performed.

The work in the field of automotive industry described in subsection 4.4 is formalized by a CIFRE contract with Renault (the PhD Student is employed by that firm since June 2005).

8. Other Grants and Activities

8.1. National initiatives

- At INRIA : Marius Tucsnak is member of the Project Committee of INRIA-Lorraine.
- In the Universities and in CNRS committees:
  – Antoine Henrot is the head of the Institut Élie Cartan de Nancy (IECN).
  – Marius Tucsnak is member of the Scientific Council of UHP
  – Our team is part of the GDR entitled "Fluid-Structure Interactions".

8.2. Associated Team

The CORIDA project is linked with a group of the University of Chile through the associated team ANCIF.

8.3. Bilateral agreements

A IFCPAR grant with the Tata Institute (Bengalooru, India).

8.4. Visits of foreign researchers

Steve Cox (Houston), Dalia Fishelov (Tel-Aviv), Pedro Freitas (Lisbonne), Jorge San Martín (Santiago), Sorin Micu (Craiova), Gerard Philippin (Laval), George Weiss (Londres).

9. Dissemination

9.1. Participation to International Conferences and Various Invitations

9.1.1. Organization of Conferences

- F. Alabau:

  ICIAM 2007, Zurich, co-organization with P. Cannarsa (Univ. Rome II) and J. Vancostenoble (Univ. Toulouse III) of a mini-symposium entitled: Control and stabilization of PDE's of interest to the applied sciences.
- M. Tucsnak: co-organizer of the International Workshop on Analysis and Control of PDE's, Pont-à-Mousson, France, June 25-29, 2007

9.1.2. Invited conferences

- F. Alabau:
  - July 2006 2nd International Workshop on Variational and Partial Differential Equations, Erice (Italy), 5–14 July 2006, *Carleman estimates for degenerate parabolic equations*.
  - March 2006 5th European-Maghreb Workshop, 28 March-1 April 2006, Hammamet (Tunisia). Plenary conference.
  - March 2006 Workshop on Partial Differential Equations and Applications, 1-3 March 2006, Université La Sapienza, Rome (Italy). Plenary Conference.
- X. Antoine:
  - Workshop on Advances in Computational Scattering, Alberta, Canada, February 2006.
- A. Henrot:
  - *Vienne (Autriche)*: Symmetry problems for nonlinear partial differential equations, January 2006.
  - *Nice*: 3rd PICOF (Problèmes inverses, Contrôle et Optimisation de Forme), April 2006.
  - *Palo Alto (USA)*: Workshop on Low Eigenvalues of Laplace and Schrödinger Operators, May 2006.
  - *Poitiers*: Sixth International Conference on Dynamical Systems, Differential Equations and Application, June 2006.
- L. Rosier
  - 8^{e} Colloque Franco-Roumain, Chambéry, August 2006
  - Workshop on PDE's, Rio de Janeiro, September 2006
  - School on Nonlinear Differential Equations, Trieste, October 2006 (Five hours course on the Control of PDE's)
  - 13th IFAC World Workshop on Control, Applications of Optimisation, Cachan, 2006.

- M. Tucsnak
  - 8^{e} Colloque Franco-Roumain, Chambéry, August 2006
  - *Poitiers*: Sixth International Conference on Dynamical Systems, Differential Equations and Application, June 2006.

9.1.3. Participation to international conferences

- T. Chambrion:
  - *November 2006:* 32nd Annual Conference of the IEEE Industrial Electronics Society (IECON-2006), Paris.

9.1.4. Invitations

- X. Antoine
  - City University of Hong-Kong, December 2005.
- L. Rosier
  - CMM, Santiago de Chile, November 2005
  - LNCC, Rio de Janeiro, September 2006
- M. Tucsnak
  - London, November 2006

9.1.5. Editorial activities and scientific committee's memberships

- M. Tucsnak is associated editor of "SIAM Journal on Control" and of "ESAIM COCV".
- M. Tucsnak is a member of the scientific committee of the ECCOMAS Conference on Computational Fluid Dynamics (ECCOMAS CFD 2006).

9.2. Teaching activities

Most of the project members are professors or assistant professors so they have an important teaching activity. We mention here only the graduate courses.

- Non linear analysis of PDE's and applications (F. Alabau);
- Scientific Computing (A. Henrot);
- Introduction to Finite Element Method (K. Ramdani)
- The Navier-Stokes Equations (M. Tucsnak);

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