IFCAM Workshop

on

Control and numerics for fluid-structure interaction problems

June 29 - July 1, 2015

Scientific committee of the Workshop

– Miguel Ángel Fernández
– Céline Grandmont
– Mythily Ramaswamy
– Jean-Pierre Raymond
– Marius Tucsnak (Chair)
– Muthusamy Vanninathan

Local organizing committee

– Praveen Chandrashekarappa, TIFR-CAM
– Sashikumar Ganesan, SERC, IISc
– Mythily Ramaswamy, TIFR-CAM
– Govindan Rangarajan, IISc
– Jean-Pierre Raymond, Univ. Paul Sabatier Toulouse III
– Muthusamy Vanninathan, TIFR-CAM

Sponsors

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Invited speakers

- Praveen Chandrashekarappa, TIFR-CAM, praveen@tifrbng.res.in
- Sylvain Ervedoza, IMT, CNRS & Université Toulouse III, ervedoza@math.univ-toulouse.fr
- Miguel Ángel Fernández, Inria, miguel.fernandez@inria.fr
- Sashikumar Ganesan, SERC, IISc, Bangalore, sashi@serc.iisc.in
- Céline Grandmont, Inria & UPMC, celine.grandmont@inria.fr
- Thirupathi Gudi, IISc Bangalore, gudi@math.iisc.ernet.in
- Alexei Lozinski, Université de Franche-Comté, alexei.lozinski@univ-fcomte.fr
- Sanjay Mittal, IIT Kanpur, smittal@iitk.ac.in
- Amiya Kumar Pani, IIT Bombay, amiya.pani08@gmail.com
- Olivier Pironneau, UPMC Paris 6, olivier.pironneau@upmc.fr
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- Thomas Richter, Heidelberg Univ., thomas.richter@iwr.uni-heidelberg.de
- Marius Tucsnak, Université de Lorraine, Marius.Tucsnak@univ-lorraine.fr
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- Enrique Zuazua, BCAM, Bilbao, zuazua@bcamath.org

Talks

Numerical implementation of feedback stabilization for Boussinesq model

Praveen Chandrashekarappa
TIFR - CAM, Bangalore

Abstract. Stabilization of fluid flows involving heat transfer is considered using the 2-D Boussinesq model. We use Riccati-based approach to compute feedback law to apply boundary control in terms of velocity, temperature and heat flux. The control is based on considering only the unstable subspace which leads to small Riccati equation. We also consider an extended system to include Dirichlet controls. The talk will present a computational framework using the automatic finite element framework FENICS. Some numerical examples will be shown to demonstrate this approach. This is joint work with Mythily Ramaswamy and Jean-Pierre Raymond.

Local controllability on constant trajectories for compressible Navier-Stokes equations

Sylvain Ervedoza
Institut de Mathématiques de Toulouse & CNRS

Abstract. In this talk I will present a recent result on the controllability of the compressible Navier-Stokes equations in dimension 3 around a constant trajectory with non-zero velocity, when the controls act on the whole boundary of the domain. The proof of this result is based on an observability inequality for the adjoint of the linearized system. The main ingredient then is to carefully combine the equations so that to consider a closed subsystem easier to deal with. This is achieved by the introduction of a new quantity corresponding to the effective viscous flux for the adjoint equations. On this subsystem, we are able to understand separately the difficulties coming from the hyperbolic part and parabolic part of the system. We thus introduce suitable Carleman estimates with weight functions following the characteristics allowing to handle the coupling terms. I will then explain how to deal with the regularity issues need for applying Schauder's fixed point argument. This is a joint work with Olivier Glass (Univ. Paris Dauphine) and Sergio Guerrero (Univ. Pierre et Marie Curie).

Unfitted mesh methods and coupling schemes for incompressible fluid-structure interaction

Miguel Ángel Fernández
Inria, Paris

Abstract. Fictitious domain/immersed boundary methods for the numerical simulation of fluid-structure interaction problems involving large interface deflections have recently seen a surge of interest. Most of the existing approaches are known to be inaccurate in space either because the fluid equations are integrated in a non-physical (fictitious) domain or because the discrete approximations are not able to reproduce weak and strong discontinuities of the physical solution. In this talk, we present alternative unfitted formulations which circumvent these accuracy issues. The kinematic/kinetic fluid-solid coupling is enforced consistently using a variant of Nitsche's method involving cut elements. Robustness with respect to arbitrary interface/element intersections is guaranteed through suitable stabilization. Whenever present, weak and strong discontinuities across the interface are allowed via suitable XFEM enrichment. Several coupling schemes, with different degrees of fluid-solid splitting (implicit, semi-implicit and explicit), will be discussed. A series of numerical tests, involving static and moving interfaces, illustrates the performance of the different methods proposed.

A variational multiscale method for finite element computations of incompressible turbulent flows with moving boundaries

Sashikumaar Ganesan and Birupaksha Pal

Numerical Mathematics and Scientific Computing
Supercomputer Education and Research Center
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Abstract

Simulations of incompressible turbulent flows are highly demanded in several industrial applications. Turbulent flows are highly unsteady flows that contain several flow scales, and the velocity field is superimposed by random velocity fluctuations. The fluid flows are described by the time-dependent incompressible Navier-Stokes equations, and the Reynolds number, which is the ratio of inertial forces to viscous forces, is used to classify laminar and turbulent flows. Despite several advances made in computational fluid dynamics (CFD), accurate modeling of turbulent flows is still very challenging.

Fluid flows around solid bodies are encountered in many practical applications, and in such cases a Kármán vortex street can occur even for a small Reynolds number, see Fig. 1 (a). Often, a moving/deforming structures are added to control the vortices that are induced due to the unsteady separation of fluid flow around bodies, see Fig. 1 (b). Apart from the other challenges associated with the modeling of turbulent flows, the moving/deforming structures make the computational domain time-depended.

In this talk, a projection based variational multiscale method with arbitrary Lagrangian-Eulerian (ALE) approach for computations of turbulent flows in time-dependent domain will be presented. After describing the developed numerical scheme in detail, an array of numerical simulations of flow over a stationary, an oscillating beam, and over a plunging aerofoil will be presented.

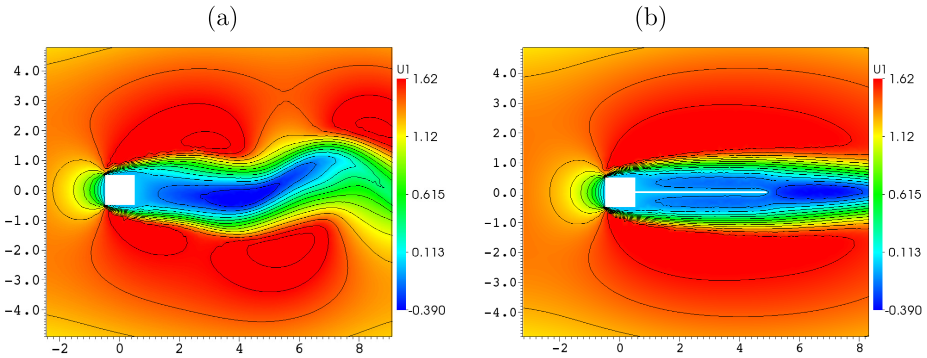

Figure 1: Streamwise velocity profile of a flow over a square (a) without beam, and (b) with beam at the dimensionless time t=25.

Existence of global strong solutions to a beam-fluid interaction system

Céline Grandmont
Inria & UPMC Paris

Abstract. We will present a result obtained in collaboration with M. Hillairet in which we study an unsteady non linear fluid-structure interaction problem. The system of equations can be viewed as simplified model to describe blood flow through viscoleastic arteries. We consider a Newtonian incompressible two-dimensional flow described by the Navier-Stokes equations set in an unknown domain depending on the displacement of a structure, which itself satisfies a linear viscoelastic beam equation. The fluid and the structure are fully coupled via interface conditions prescribing the continuity of the velocities at the fluid-structure interface and the action-reaction principle. We prove that strong solutions to this problem are global-in-time. We obtain in particular that contact between the viscoleastic wall and the bottom of the fluid cavity does not occur in finite time.

On the Dirichlet boundary optimal control problem and its finite element approximation

Thirupathi Gudi
Department of Mathematics, IISc, Bangalore

Abstract. In this talk, we will discuss an energy space based approach for the Dirichlet boundary optimal control problem. We show that the control, state and co-state functions exhibit sufficient regularity. Based on this approach, we design a finite element method and prove optimal order error estimates in the energy and L^2 norms. A posteriori error estimates for the development of adaptive algorithm will be presented. If time permits, we will discuss some applications to convection-diffusion problems discretized by the SUPG method. Numerical experiments will be shown to illustrate the theoretical results.

Stabilized fictitious domain approaches for fluid/structure interaction

Alexei Lozinski
Laboratoire de Mathématiques, Université de Franche-Comté

Abstract. Fictitious domain methods permit to perform a simulation of a flow in a domain changing in time without constantly modifying the mesh. The current tendency in constructing such methods is to to use the trace of the global mesh on the interface for the finite element space of Lagrange multipliers (instead of constructing another mesh on the interface as in the classical version of the method) and to perform integration on the current flow domain in the variational formulation. The optimal accuracy can be thus achieved provided appropriate stabilization terms are added. We shall present our recently proposed variant of such method (with Barbosa-Hughes stabilization) and compare it with other methods available in the literature (interior penalization, local L^2 projections). We shall also discuss the possibilities to avoid the calculation of integrals over cut mesh elements which is cumbersome to implement. We illustrate the capacities of the method by applying it to the incompressible Stokes or Navier-Stokes equations coupled with a moving rigid solid. In the Navier-Stokes case, special attention is paid to the approximation of the time derivative in the moving domain.
This is a joint work with Sébastien Court and Michel Fournié.

Lock-in in vortex-induced vibrations

Sanjay Mittal
Aerospace Engineering Department, IIT Kanpur

Abstract. The phenomenon of lock-in in vortex-induced vibrations of a circular cylinder is investigated in the laminar flow regime ($20 < Re < 100$). Direct time integration (DTI) and linear stability analysis (LSA) of the governing equations are carried out via a stabilized finite element method. Using the metrics that have been proposed in earlier studies, the lock-in regime is identified from the results of DTI. The LSA yields the eigenmodes of the coupled fluid-structure system, the associated natural frequencies and the stability of the steady state. A linearly unstable system, in the absence of non-linear effects, achieves large oscillation amplitude at sufficiently large times. However, the non-linear terms saturate the response of the system to a limit cycle. For sub-critical Re, the occurrence of lock-in coincides with the linear instability of the fluid-structure system. For super-critical Re, even though the aero-elastic system is unstable for all reduced velocities (U^*) lock-in occurs only for a finite range of U*. We present a method to estimate the time beyond which the non-linear effects are expected to be significant. It is observed that much of the growth in the amplitude of cylinder oscillation takes place in the linear regime. The response of the cylinder at the end of the linear regime is found to depend on the energy ratio, E_r, of the unstable eigenmode. E_r is defined as the fraction of the total energy of the eigenmode that is associated with the kinetic and potential energy of the structure. DTI initiated from eigenmodes that are linearly unstable and whose energy ratio is above a certain threshold value lead to lock-in. Interestingly, during lock-in, the natural frequency of the fluid-structure system drifts towards a value that is closer to the natural frequency of the oscillator in vacuum. The concept of added mass coefficient and the phase angle between the cylinder displacement and lift is extended for an eigenmode. While the added mass coefficient modifies the natural frequency of the oscillator in fluid, the phase angle controls the direction of energy transfer between the fluid and the structure.

Kelvin-Voigt Viscoelastic Model : Some theoretical and Computational Issues

Amiya Kumar Pani
Department of Mathematics, IIT Bombay

An Overview of Some Fluid-Structure Algorithms with Some Personal Contributions

Olivier Pironneau
Laboratoire Jacques Louis Lions, UPMC Paris 6

Abstract. Fluid-Structure systems in interaction can be approached either by an all solid approach as in Gonzalez-Simo [4], etc with a Lagrangian frame and nonlinear displacement or as an all Multi-fluids method as in Peskin [8], Coupez [3], Boffi-Cavallini-Gastaldi [1] etc., or as two separate mechanical systems in interaction as in Quarteroni et al. [6].

We shall survey some mathematical and algorithmic results for these 3 approaches and comment on their assets and difficulties, leaving unsurveyed all iterative algorithms based on fluid-structure decoupling and the added mass riddle.

When the structure is a Koiter shell we propose and analyse a simplified fluid-structure coupled model for flows with compliant walls. As in Nobile-Vergara [7] the wall reaction to the fluid is modelled by a small displacement visco-elastic shell where the tangential stress components and displacements are neglected. We show that within this small displacement approximation it is licit to neglect motion of the geometry, at least when the boundary is locally C^2. Such simplifications lead to a model which we shall show to be well posed and for which a semi-implicit time discretisation can be shown to converge [2]. We present some numerical results and a comparison with a standard test case taken from hemodynamics. The model is more stable and less computer demanding than full models with moving domains. Thus we are able to solve an optimization problem for a stent within a 3D artery using optimal control and a gradient method.

References

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[3] Th. Coupez, L. Silva, E. Hachem, Implicit Boundary and Adaptive Anisotropic Meshes, S. Peretto, L. Formaggia eds. *New challenges in Grid Generation and Adaptivity for Scientific Computing.* SEMA-SIMAI Springer series, vol 5, 2015.

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Local stabilization of one dimensional Compressible Navier-Stokes system around constant steady states

Mythily Ramaswamy
TIFR - CAM, Bangalore

Abstract. Navier-Stokes system for the density and velocity of a compressible fluid in a bounded interval will be considered. Local stabilization results for the solution in a neighborhood of constant steady states will be described. The different exponential decays in the two cases of null and non-null velocity cases will be analyzed.

Local stabilization of fluid-structure models

Jean-Pierre Raymond
Institut de Mathématiques de Toulouse, Université Paul Sabatier Toulouse III

Abstract. We shall address the problem of stabilizing a fluid flow modeled by the incompressible Navier-Stokes equations by boundary deformations. Next, we apply this approach to stabilize a system coupling the incompressible Navier-Stokes equations with the Lamé system of linear elasticity by a distributed control acting only in the elasticity equation, localized in a neighborhood of the fluid-structure interface. For regular initial data, small enough, we prove the existence of L^2 controls stabilizing the coupled system with an arbitrarily prescribed exponential decay rate. This part is a joint work with M. Vanninathan. We shall also present numerical results of stabilization of fluid flows by boundary deformations. This second part is a joint work with M. Fournié and M. Ndiaye.

Goal-Oriented Adaptivity and Optimization for Fluid-Structure Interactions

Thomas Richter
University of Heidelberg

Abstract. In this talk, we present a sensitivity based framework for adaptive finite element simulations and optimization of fluid-structure interactions.

The talk will be split into three parts. First, we will introduce basic concepts of sensitivity analysis for error estimation, mesh adaptivity and gradient based optimization tools. Second, we will derive dual formulations for fluid-structure interactions. With the help of linearized adjoint problems, we will be able to compute sensitivities with respect to technical goal values, such as drag- or lift-coefficients, stress measures or flow rates. Finally, we will use these adjoint solutions to derive reliable error estimates controlling mesh adaptivity and to guide simple gradient based optimization schemes.

Scanning control of viscous fluids and fluid-structure interactions

Marius Tucsnak
Université de Lorraine

Abstract. We investigate the control of systems modelling the interaction of viscous fluids with rigid bodies immersed in it, with focus on the case when the control acts only on the rigid bodies. We obtain strong stabilization results in the general case and controllability for a simplified model.

Some Simplified Models in Fluid-Structure Interaction and controllability

Vanninathan
TIFR - CAM, Bangalore

Abstract. Motivated by applications, a class of simplified models of fluid-structure interaction is introduced. A typical configuration would be an oscillator immersed inside a fluid.This talk is devoted to one particular model from this class and its controllability properties.This is investigated using various methods such as HUM,frequency domain method etc. Ultimate goal is to show that the model is exactly controllable by means of control acting only on fluid part without any control near the oscillator.This can be done in some cases.

Large time asymptotics, numerics, and control for hybrid PDE-ODE systems

Enrique Zuazua
Ikerbasque & BCAM & Humboldt-Erlangen
Bilbao - Basque Country - Spain

Abstract. Most often, relevant models in fluid-structure interaction involve the coupling of Partial Differential Equations (PDE) with Ordinary Differential Equations (ODE). Hyperbolic conservation laws do not seem to present that structure. But in fact they do, because of the implicit coupling of the PDE component with the classical Rankine-Hugoniot condition for the velocity of shocks. Shock formation, in fact, also allows different solutions to collapse in future times, providing a paradigmatic negative example of semigroup that does not enjoy the property of backward uniqueness. This very much affects the solvability of some of the most elementary optimal control problems, such as that of the inverse design. We shall present some recent developments on the problem of finding the possible multiple inverse designs. The efficiency of numerical algorithms developed with this purpose is very much related to whether they preserve the dynamic properties of solutions in long time intervals. This issue will also be discussed for hyperbolic conservation laws and Kolmogorov equations. The content of this lecture is based on joint work in collaboration with L. Gosse and A. Porretta.

	June 29	June 30	July 1
9h30 – 10h30	9h25 Opening Thomas Richter	Enrique Zuazua	Sanjay Mittal
10h30 – 11h	Coffee Break	Coffee Break	Coffee Break
11h – 12h	Céline Grandmont	Sylvain Ervedoza	Miguel Fernandez
12h – 13h	Muthusamy Vanninathan	Mythily Ramaswamy	Olivier Pironneau
13h – 14h	Lunch	Lunch	Lunch
14h – 15h	Thirupathi Gudi	Sashikumar Ganesan	Praveen Chandrashekarappa
15h – 16h	Amiya Kumar Pani	Alexei Lozinski	Jean-Pierre Raymond
16h30 – 17h	Coffee Break	Coffee Break	Coffee Break
19h30-22h	Social dinner IISc Math. Dept.		

Registration will be open before 9 a.m., on Monday, June 29.

A social dinner will be organized on Monday evening at the Terrace of The Math. Dept., IISc.