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Project-Team REO

Numerical simulation of biological flows

IN COLLABORATION WITH: Laboratoire Jacques-Louis Lions

RESEARCH CENTER
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THEME
Modeling and Control for Life Sciences

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Project-Team REO

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2. Overall Objectives

2.1. Overall Objectives

REO is a joint project of the Inria Research Center of Paris-Rocquencourt and the Jacques-Louis Lions Laboratory (LJLL) of the Pierre and Marie Curie University (Paris 6) and CNRS (UMR7598). Its research activities are aimed at

- modeling some aspects of the cardiovascular and respiratory systems, both in normal and pathological states;
- developing and analyzing efficient, robust and reliable numerical methods for the simulation of those models;
- developing simulation software to guide medical decision and to design more efficient medical devices.

3. Research Program

3.1. Multiphysics modeling

In large vessels and in large bronchi, blood and air flows are generally supposed to be governed by the incompressible Navier-Stokes equations. Indeed in large arteries, blood can be supposed to be Newtonian, and at rest air can be modeled as an incompressible fluid. The cornerstone of the simulations is therefore a Navier-Stokes solver. But other physical features have also to be taken into account in simulations of biological flows, in particular fluid-structure interaction in large vessels and transport of sprays, particles or chemical species.

3.1.1. Fluid-structure interaction

Fluid-structure coupling occurs both in the respiratory and in the circulatory systems. We focus mainly on blood flows since our work is more advanced in this field. But the methods developed for blood flows could be also applied to the respiratory system.

Here "fluid-structure interaction" means a coupling between the 3D Navier-Stokes equations and a 3D (possibly thin) structure in large displacements.

The numerical simulations of the interaction between the artery wall and the blood flows raise many issues: (1) the displacement of the wall cannot be supposed to be infinitesimal, geometrical nonlinearities are therefore present in the structure and the fluid problem have to be solved on a moving domain (2) the densities of the artery walls and the blood being close, the coupling is strong and has to be tackled very carefully to avoid numerical instabilities, (3) "naive" boundary conditions on the artificial boundaries induce spurious reflection phenomena.

Simulation of valves, either at the outflow of the cardiac chambers or in veins, is another example of difficult fluid-structure problems arising in blood flows. In addition, very large displacements and changes of topology (contact problems) have to be handled in those cases.

Due to stability reasons, it seems impossible to successfully apply in hemodynamics the explicit coupling schemes used in other fluid-structure problems, like aeroelasticity. As a result, fluid-structure interaction in biological flows raise new challenging issues in scientific computing and numerical analysis : new schemes have to be developed and analyzed.

We have proposed and analyzed over the last few years several efficient fluid-structure interaction algorithms. This topic remains very active. We are now using these algorithms to address inverse problems in blood flows to make patient specific simulations (for example, estimation of artery wall stiffness from medical imaging).

3.1.2. Aerosol

Complex two-phase fluids can be modeled in many different ways. Eulerian models describe both phases by physical quantities such as the density, velocity or energy of each phase. In the mixed fluid-kinetic models, the biphasic fluid has one dispersed phase, which is constituted by a spray of droplets, with a possibly variable size, and a continuous classical fluid.

This type of model was first introduced by Williams [68] in the frame of combustion. It was later used to develop the Kiva code [58] at the Los Alamos National Laboratory, or the Hesione code [63], for example. It has a wide range of applications, besides the nuclear setting: diesel engines, rocket engines [61], therapeutic sprays, *etc.* One of the interests of such a model is that various phenomena on the droplets can be taken into account with an accurate precision: collision, breakups, coagulation, vaporization, chemical reactions, *etc.*, at the level of the droplets.

The model usually consists in coupling a kinetic equation, that describes the spray through a probability density function, and classical fluid equations (typically Navier-Stokes). The numerical solution of this system relies on the coupling of a method for the fluid equations (for instance, a finite volume method) with a method fitted to the spray (particle method, Monte Carlo).

We are mainly interested in modeling therapeutic sprays either for local or general treatments. The study of the underlying kinetic equations should lead us to a global model of the ambient fluid and the droplets, with some mathematical significance. Well-chosen numerical methods can give some tracks on the solutions behavior and help to fit the physical parameters which appear in the models.

3.2. Multiscale modeling

Multiscale modeling is a necessary step for blood and respiratory flows. In this section, we focus on blood flows. Nevertheless, similar investigations are currently carried out on respiratory flows.

3.2.1. Arterial tree modeling

Problems arising in the numerical modeling of the human cardiovascular system often require an accurate description of the flow in a specific sensible subregion (carotid bifurcation, stented artery, *etc.*). The description of such local phenomena is better addressed by means of three-dimensional (3D) simulations, based on the numerical approximation of the incompressible Navier-Stokes equations, possibly accounting for compliant (moving) boundaries. These simulations require the specification of boundary data on artificial boundaries that have to be introduced to delimit the vascular district under study. The definition of such boundary conditions is critical and, in fact, influenced by the global systemic dynamics. Whenever the boundary data is not available from accurate measurements, a proper boundary condition requires a mathematical description of the action of the reminder of the circulatory system on the local district. From the computational point of view, it is not affordable to describe the whole circulatory system keeping the same level of detail. Therefore, this mathematical description relies on simpler models, leading to the concept of *geometrical multiscale* modeling of the circulation [64]. The underlying idea consists in coupling different models (3D, 1D or 0D) with a decreasing level of accuracy, which is compensated by their decreasing level of computational complexity.

The research on this topic aims at providing a correct methodology and a mathematical and numerical framework for the simulation of blood flow in the whole cardiovascular system by means of a geometric multiscale approach. In particular, one of the main issues will be the definition of stable coupling strategies between 3D and reduced order models.

To model the arterial tree, a standard way consists of imposing a pressure or a flow rate at the inlet of the aorta, *i.e.* at the network entry. This strategy does not allow to describe important features as the overload in the heart caused by backward traveling waves. Indeed imposing a boundary condition at the beginning of the aorta artificially disturbs physiological pressure waves going from the arterial tree to the heart. The only way to catch this physiological behavior is to couple the arteries with a model of heart, or at least a model of left ventricle.

A constitutive law for the myocardium, controlled by an electrical command, has been developed in the CardioSense3D project [1]. One of our objectives is to couple artery models with this heart model.

A long term goal is to achieve 3D simulations of a system including heart and arteries. One of the difficulties of this very challenging task is to model the cardiac valves. To this purpose, we investigate a mix of arbitrary Lagrangian Eulerian and fictitious domain approaches or x-fem strategies, or simplified valve models based on an immersed surface strategy.

3.2.2. Heart perfusion modeling

The heart is the organ that regulates, through its periodical contraction, the distribution of oxygenated blood in human vessels in order to nourish the different parts of the body. The heart needs its own supply of blood to work. The coronary arteries are the vessels that accomplish this task. The phenomenon by which blood reaches myocardial heart tissue starting from the blood vessels is called in medicine perfusion. The analysis of heart perfusion is an interesting and challenging problem. Our aim is to perform a three-dimensional dynamical numerical simulation of perfusion in the beating heart, in order to better understand the phenomena linked to perfusion. In particular the role of the ventricle contraction on the perfusion of the heart is investigated as well as the influence of blood on the solid mechanics of the ventricle. Heart perfusion in fact implies the interaction between heart muscle and blood vessels, in a sponge-like material that contracts at every heartbeat via the myocardium fibers.

Despite recent advances on the anatomical description and measurements of the coronary tree and on the corresponding physiological, physical and numerical modeling aspects, the complete modeling and simulation of blood flows inside the large and the many small vessels feeding the heart is still out of reach. Therefore, in order to model blood perfusion in the cardiac tissue, we must limit the description of the detailed flows at a given space scale, and simplify the modeling of the smaller scale flows by aggregating these phenomena into macroscopic quantities, by some kind of “homogenization” procedure. To that purpose, the modeling of the fluid-solid coupling within the framework of porous media appears appropriate.

Poromechanics is a simplified mixture theory where a complex fluid-structure interaction problem is replaced by a superposition of both components, each of them representing a fraction of the complete material at every point. It originally emerged in soils mechanics with the work of Terzaghi [67], and Biot [59] later gave a description of the mechanical behavior of a porous medium using an elastic formulation for the solid matrix, and Darcy’s law for the fluid flow through the matrix. Finite strain poroelastic models have been proposed (see references in [60]), albeit with *ad hoc* formulations for which compatibility with thermodynamics laws and incompressibility conditions is not established.

3.2.3. Tumor and vascularization

The same way the myocardium needs to be perfused for the heart to beat, when it has reached a certain size, tumor tissue needs to be perfused by enough blood to grow. It thus triggers the creation of new blood vessels (angiogenesis) to continue to grow. The interaction of tumor and its micro-environment is an active field of research. One of the challenges is that phenomena (tumor cell proliferation and death, blood vessel adaptation, nutrient transport and diffusion, etc) occur at different scales. A multi-scale approach is thus being developed to tackle this issue. The long term objective is to predict the efficiency of drugs and optimize therapy of cancer.

[1] http://www-sop.inria.fr/CardioSense3D/

3.2.4. Respiratory tract modeling

We aim at developing a multiscale model of the respiratory tract. Intraprenchymal airways distal from generation 7 of the tracheabronchial tree (TBT), which cannot be visualized by common medical imaging techniques, are modeled either by a single simple model or by a model set according to their order in TBT. The single model is based on straight pipe fully developed flow (Poiseuille flow in steady regimes) with given alveolar pressure at the end of each compartment. It will provide boundary conditions at the bronchial ends of 3D TBT reconstructed from imaging data. The model set includes three serial models. The generation down to the pulmonary lobule will be modeled by reduced basis elements. The lobular airways will be represented by a fractal homogenization approach. The alveoli, which are the gas exchange loci between blood and inhaled air, inflating during inspiration and deflating during expiration, will be described by multiphysics homogenization.

4. Application Domains

4.1. Blood flows

Cardiovascular diseases like atherosclerosis or aneurysms are a major cause of mortality. It is generally admitted that a better knowledge of local flow patterns could improve the treatment of these pathologies (although many other biophysical phenomena obviously take place in the development of such diseases). In particular, it has been known for years that the association of low wall shear stress and high oscillatory shear index give relevant indications to localize possible zones of atherosclerosis. It is also known that medical devices (graft or stent) perturb blood flows and may create local stresses favorable with atherogenesis. Numerical simulations of blood flows can give access to this local quantities and may therefore help to design new medical devices with less negative impacts. In the case of aneurysms, numerical simulations may help to predict possible zones of rupture and could therefore give a guide for treatment planning.

In clinical routine, many indices are used for diagnosis. For example, the size of a stenosis is estimated by a few measures of flow rate around the stenosis and by application of simple fluid mechanics rules. In some situations, for example in the case a sub-valvular stenosis, it is known that such indices often give false estimations. Numerical simulations may give indications to define new indices, simple enough to be used in clinical exams, but more precise than those currently used.

It is well-known that the arterial circulation and the heart (or more specifically the left ventricle) are strongly coupled. Modifications of arterial walls or blood flows may indeed affect the mechanical properties of the left ventricle. Numerical simulations of the arterial tree coupled to the heart model could shed light on this complex relationship.

One of the goals of the REO team is to provide various models and simulation tools of the cardiovascular system. The scaling of these models will be adapted to the application in mind: low resolution for modeling the global circulation, high resolution for modeling a small portion of vessel.

4.2. Respiratory tracts

Breathing, or “external” respiration (“internal” respiration corresponds to cellular respiration) involves gas transport though the respiratory tract with its visible ends, nose and mouth. Air streams then from the pharynx down to the trachea. Food and drink entry into the trachea is usually prevented by the larynx structure (epiglottis). The trachea extends from the neck into the thorax, where it divides into right and left main bronchi, which enter the corresponding lungs (the left being smaller to accommodate the heart). Inhaled air is then convected in the bronchus tree which ends in alveoli, where gaseous exchange occurs. Surfactant reduces the surface tension on the alveolus wall, allowing them to expand. Gaseous exchange relies on simple diffusion on a large surface area over a short path between the alveolus and the blood capillary under concentration gradients between alveolar air and blood. The lungs are divided into lobes (three on the right, two on the left) supplied by lobar bronchi. Each lobe of the lung is further divided into segments (ten segments of the right lung and eight of the left). Inhaled air contains dust and debris, which must be filtered, if possible, before they reach the alveoli. The tracheobronchial tree is lined by a layer of sticky mucus, secreted by the epithelium. Particles which hit the side wall of the tract are trapped in this mucus. Cilia on the epithelial cells move the mucous continually towards the nose and mouth.

Each lung is enclosed in a space bounded below by the diaphragm and laterally by the chest wall and the mediastinum. The air movement is achieved by alternately increasing and decreasing the chest pressure (and volume). When the airspace transmural pressure rises, air is sucked in. When it decreases, airspaces collapse and air is expelled. Each lung is surrounded by a pleural cavity, except at its hilum where the inner pleura give birth to the outer pleura. The pleural layers slide over each other. The tidal volume is nearly equal to 500 ml.

The lungs may fail to maintain an adequate supply of air. In premature infants surfactant is not yet active. Accidental inhalation of liquid or solid and airway infection may occur. Chronic obstructive lung diseases and lung cancers are frequent pathologies and among the three first death causes in France.

One of the goals of REO team in the ventilation field is to visualize the airways (virtual endoscopy) and simulate flow in image-based 3D models of the upper airways (nose, pharynx, larynx) and the first generations of the tracheobronchial tree (trachea is generation 0), whereas simple models of the small bronchi and alveoli are used (reduced-basis element method, fractal homogenization, multiphysics homogenization, lumped parameter models), in order to provide the flow distribution within the lung segments.

4.3. Cardiac electrophysiology

The purpose is to simulate the propagation of the action potential in the heart. A lot of works has already been devoted to this topic in the literature (see *e.g.* [62], [66], [65] and the references therein), nevertheless there are only very few studies showing realistic electrocardiograms obtained from partial differential equations models. Our goal is to find a compromise between two opposite requirements: on the one hand, we want to use predictive models, and therefore models based on physiology, on the other hand, we want to use models simple enough to be parametrized (in view of patient-specific simulations). One of the goal is to use our ECG simulator to address the inverse problem of electrocardiology. In collaboration with the Macs/M3disym project-team, we are interested in the electromechanical coupling in the myocardium. We are also interested in various clinical and industrial issues related to cardiac electrophysiology, in particular the simulation of experimental measurement of the field potential of cardiac stem cells in multi-electrode arrays.

5. New Software and Platforms

5.1. FELiScE

Participants: Grégory Arbia, Cédric Doucet, Miguel Ángel Fernández Varela, Justine Fouchet-Incaux, Benoit Fabrèges, Axel Fourmont, Jean-Frédéric Gerbeau [correspondant], Mikel Landajuela Larma, Damiano Lombardi, Elisa Schenone, Saverio Smaldone, Marina Vidrascu, Irène Vignon-Clementel, Vincent Martin.

FELiScE – standing for "Finite Elements for Life Sciences and Engineering" – is a finite element code which the M3DISYM and REO project-teams have decided to jointly develop in order to build up on their respective experiences concerning finite element simulations. One specific objective of this code is to provide in a unified software environment all the state-of-the-art tools needed to perform simulations of the complex respiratory and cardiovascular models considered in the two teams – namely involving fluid and solid mechanics, electrophysiology, and the various associated coupling phenomena. FELISCE is written in C++, and may be later released as an opensource library.

It was registered in July 2014 at the *Agence pour la Protection des Programmes* under the Inter Deposit Digital Number IDDN.FR.001.350015.000.S.P.2014.000.10000.

Gforge web site: https://gforge.inria.fr/projects/felisce/

5.2. LiFE-V library

Participants: Miguel Ángel Fernández Varela [correspondant], Jean-Frédéric Gerbeau.

LiFE-V [2] is a finite element library providing implementations of state of the art mathematical and numerical methods. It serves both as a research and production library. LiFE-V is the joint collaboration between three institutions: Ecole Polytechnique Fédérale de Lausanne (CMCS) in Switzerland, Politecnico di Milano (MOX) in Italy and Inria (REO) in France. It is a free software under LGPL license.

5.3. SHELDDON

Participant: Marina Vidrascu [correspondant].

SHELDDON (SHELls and structural Dynamics with DOmain decomposition in Nonlinear analysis) is a finite element library based on the Modulef package which contains shell elements, nonlinear procedures and PVM subroutines used in domain decomposition or coupling methods, in particular fluid-structure interaction.

Gforge web site: https://gforge.inria.fr/projects/shelddon

6. New Results

6.1. Highlights of the Year

- Jimmy Mullaert was awarded the best poster prize at the conference Canum 2014.
- Jessica Oakes was awarded a University of California Presidential Postdoctoral Fellowship.
- Jessica Oakes won a young investigator award at the "4th International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease".

6.2. Mathematical and numerical analysis of fluid-structure interaction problems

Participants: Benoit Fabrèges, Miguel Ángel Fernández Varela, Mikel Landajuela Larma, Jimmy Mullaert, Marina Vidrascu.

- In [54] we introduce two new classes of numerical methods for the solution of incompressible fluid/thin-walled structure interaction problems with unfitted meshes. The semi-implicit or explicit nature of the splitting in time is dictated by the order in which the spatial and time discretizations are performed. Stability and optimal accuracy are achieved without restrictive CFL conditions or correction iterations. Results presented by M. Landajuela at the 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona (Spain).
- In [47] we introduce a class of fully decoupled time-marching schemes (velocity-pressure-displacement splitting) for the coupling of an incompressible fluid with a thin-walled viscoelastic structure. The time splitting combines a projection method in the fluid with a specific Robin-Neumann treatment of the interface coupling. A priori energy estimates guaranteeing unconditional stability are established for some of the schemes. The accuracy and performance of the methods proposed is illustrated by a thorough numerical study.
- We have performed an a priori error analysis for the generalized Robin-Neumann explicit coupling schemes introduced in [30]. The analysis confirms the $\mathcal{O}(\tau^{2^{r-1}}/h^{\frac{1}{2}})$ error perturbation anticipated by the numerical evidence of [30]. Another fundamental result of this work is that the h-non-uniformity of the splitting error is not a consequence of the mass-lumping approximation (which simply dictates the explicit or semi-implicit nature of the coupling scheme). The analysis indicates that the genesis of the $\mathcal{O}(h^{-\frac{1}{2}})$ is the non-uniformity of discrete viscoelastic operator, which is a consequence of thick-walled character of the solid. These results have been reported in [48] and presented by M.A. Fernández at the 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona (Spain).

[2] http://www.lifev.org/

- We consider the extension of the Nitsche-XFEM method to fluid-structure interaction problems involving a thin-walled elastic structure (Lagrangian formalism) immersed in an incompressible fluid (Eulerian formalism). The fluid domain is discretized with an unstructured mesh not fitted to the solid mid- surface mesh. Weak and strong discontinuities across the interface are allowed for the velocity and pressure, respectively. 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 a ghost penalty stabilization. Different coupling schemes, either fully implicit or loosely coupled, are proposed. Several numerical examples, involving static and moving interfaces, illustrate the performance of the methods. A paper in collaboration with F. Alauzet (project-team Gamma3) is under preparation. Results presented by B. Fabrèges at the 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona (Spain).

6.3. Numerical methods for biological flows

Participants: Grégory Arbia, Benoit Fabrèges, Miguel Ángel Fernández Varela, Justine Fouchet-Incaux, Jean-Frédéric Gerbeau, Céline Grandmont, Sanjay Pant, Saverio Smaldone, Marc Thiriet, Irène Vignon-Clementel.

- In [19] We consider the problem of estimating the stiffness of an artery wall using a data assimilation method applied to a 3D fluid-structure interaction (FSI) model. We briefly present the FSI model, the data assimilation procedure based on a reduced order Unscented Kalman filter, and the segmentation algorithm. We then present two examples of the procedure using real data. First, we estimate the stiffness distribution of a silicon rubber tube from image data. Second, we present the estimation of aortic wall stiffness from real clinical data.
- In [29], we propose a new approach to the loosely coupled time-marching of a fluid-fluid interaction problems involving the incompressible Navier-Stokes equations. The methods combine a specific explicit Robin-Robin treatment of the interface coupling with a weakly consistent interface pressure stabilization in time. A priori energy estimates guaranteeing stability of the splitting are obtained for a total pressure formulation of the coupled problem. The performance of the proposed schemes is illustrated on several numerical experiments related to simulation of aortic blood flow.
- In [55] we investigate the stability of numerical schemes that are classically used in the simulation of airflows and blood flows. The geometrical complexity of the networks in which air/blood flows leads to a classical decomposition of two areas: a truncated 3D geometry corresponding to the largest contribution of the domain, and a 0D part connected to the 3D part, modelling air/blood flows in smaller airways/vessels. The resulting Navier-Stokes system in the 3D truncated part may involve non-local boundary conditions, deriving from a mechanical model. For various 3D/0D coupled models, different discretization processes are presented and analyzed in terms of numerical stability, highlighting strong differences according to the regimes that are considered. In particular, two main stability issues are investigated: first the coupling between the 3D and the 0D part for which implicit or explicit strategies are studied and, second, the question of estimating the amount of kinetic energy entering the 3D domain because of the artificial boundaries. The second issue has been also the subject of a review [31].
- In [31] we deal with numerical simulations of incompressible Navier-Stokes equations in truncated domain. In this context, the formulation of these equations has to be selected carefully in order to guarantee that their associated artificial boundary conditions are relevant for the considered problem. In this paper, we review some of the formulations proposed in the literature, and their associated boundary conditions. Some numerical results linked to each formulation are also presented. We compare different schemes, giving successful computations as well as problematic ones, in order to better understand the difference between these schemes and their behaviours dealing with systems involving Neumann boundary conditions. We also review two stabilization methods which aim at suppressing the instabilities linked to these natural boundary conditions.

- In [40], we propose a framework for Windkessel parameter estimation in a 0D representation of the 3D fluid-flow domain. Parameters are estimated from uncertain measurements through a sequential approach, and the 0D representation is iteratively improved through 3D-CFD simulations. The application of generalized sensitivity functions to assess parameter correlation and to ascertain the measurement set needed to avoid identifiability problems is also presented through representative test cases. This method, which is capable of handling non-simultaneous measurements, is demonstrated and validated for a patient-specific case of aortic coarctation.
- In [17] we perform the first patient-specific pulmonary hemodynamics 3D-0D modeling before single ventricle stage 2 surgery. 0D parameters are automatically tuned to match flow and pressure clinical measurements that are not taken where 3D boundary conditions need to be specified. This work on six patients demonstrates how simulations can help to check the coherence of clinical data or provide insights to clinicians that are otherwise difficult to measure, such as in the presence of kinks.
- In [25] we study a case of post single ventricle stage 2 surgery with the three following aims: (i) to show how to build a patient-specific model describing the hemodynamics in the presence of collaterals, using patient-specific clinical data collected at different times; (ii) to use this model to perform virtual collateral occlusion for quantitative hemodynamics prediction; and (iii) to compare predicted hemodynamics with post-operative measurements.

6.4. Numerical methods for cardiac electrophysiology

Participants: Muriel Boulakia, Jean-Frédéric Gerbeau, Damiano Lombardi, Elisa Schenone.

- In [33], a reduced-order method based on Approximated Lax Pairs (ALP) is applied to the integration of electrophysiology models. These are often high- dimensional parametric equation systems, challenging from a model reduction stand- point. The method is tested on two and three dimensional test-cases, of increasing complexity. The solutions are compared to the ones obtained by a finite element. The reduced-order simulation of pseudo-electrocardiograms based on ALP is proposed in the last part.
- In [21], we address the question of the discretization of Stochastic Partial Differential Equations (SPDE) for excitable media. Working with SPDE driven by colored noise, we consider a numerical scheme based on finite differences in time (Euler-Maruyama) and finite elements in space. Motivated by biological considerations, we study numerically the emergence of reentrant patterns in excitable systems such as the Barkley or Mitchell-Schaeffer models.

6.5. Lung and respiration modeling

Participants: Laurent Boudin, Muriel Boulakia, Céline Grandmont, Jessica Oakes, Ayman Moussa, Irène Vignon-Clementel.

- In [20], we consider the non-reactive fully elastic Boltzmann equation for mixtures. We deduce that, under the standard diffusive scaling, its limit for vanishing Mach and Knudsen numbers is the Maxwell-Stefan model for a multicomponent gaseous mixture.
- In [49], we first deal with the modelling and the discretization of an aerosol evolving in the air, in the respiration framework, within a domain which can be fixed or moving. We also investigate basic numerical properties of the numerical code which was developped, and also focus on the influence of the aerosol on the airflow.
- In [38], the aim of the study was to determine susceptibility differences between healthy and emphysematous rats exposed to airborne particles. To do this, we performed animal exposure experimenters and measured particle deposition concentrations with Magnetic Resonance Imaging. We showed that overall deposition was significantly higher in the elastase-treated rats compared to the healthy ones, suggesting enhanced susceptibility to airborne particles in diseased lungs. Current work aims at integrating such experimental data into modeling [39] and compare numerical simulations with experiments. To extend particle modeling to expiration, a 1D particle transport model is under development [44].

While it is known that the retention of fine particles is less in microgravity (uG) compared to normal gravity (1G) levels, it was unknown the spatial relationship of deposited particles. In [26], rats were exposed to 1 micron diameter particles on the NASA uG airplane and compared to rats exposed in 1G. We found that the ratio of deposited particles in the central airways compared to the peripheral ones, was significantly less in the uG than in 1G, indicating enhanced deposition in the periphery. This data suggests that toxicology effects of exposure to Moon dust may not be insignificant.

- In [51], we establish stability estimates for the unique continuation property of the nonstationary Stokes problem. These estimates hold without prescribing boundary conditions and are of logarithmic type. They are obtained thanks to Carleman estimates for parabolic and elliptic equations. Then, these estimates are applied to an inverse problem where we want to identify a Robin coefficient defined on some part of the boundary from measurements available on another part of the boundary.

6.6. Miscellaneous

Participants: Jean-Frédéric Gerbeau, Damiano Lombardi, Marina Vidrascu.

- in [32] a reduced-order model algorithm, called ALP, is proposed to solve nonlinear evolution partial differential equations. It is based on approximations of generalized Lax pairs. Contrary to other reduced-order methods, like Proper Orthogonal Decomposition, the basis on which the solution is searched for evolves in time according to a dynamics specific to the problem. It is therefore well-suited to solving problems with progressive front or wave propagation. Another difference with other reduced-order methods is that it is not based on an off-line / on-line strategy. Numerical examples are shown for the linear advection, KdV and FKPP equations, in one and two dimensions.
- in [41] we propose a direct method for computing modal coupling coefficients - due to geometrically nonlinear effects - for thin shells vibrating at large amplitude and discretized by a finite element (FE) procedure. These coupling coefficients arise when considering a discrete expansion of the unknown displacement onto the eigenmodes of the linear operator. The evolution problem is thus projected onto the eigenmodes basis and expressed as an assembly of oscillators with quadratic and cubic nonlinearities. The nonlinear coupling coefficients are directly derived from the finite element formulation, with specificities pertaining to the shell elements considered, namely, here elements of the "Mixed Interpolation of Tensorial Components" family (MITC). Therefore, the computation of coupling coefficients, combined with an adequate selection of the significant eigenmodes, allows the derivation of effective reduced-order models for computing - with a continuation procedure - the stable and unstable vibratory states of any vibrating shell, up to large amplitudes. The procedure is illustrated on a hyperbolic paraboloid panel. Bifurcation diagrams in free and forced vibrations are obtained. Comparisons with direct time simulations of the full FE model are given. Finally, the computed coefficients are used for a maximal reduction based on asymptotic nonlinear normal modes (NNMs), and we find that the most important part of the dynamics can be predicted with a single oscillator equation.
- in [53] we deal with the following data assimilation problem: construct an analytical approximation of a numerical constitutive law in three-dimensional nonlinear elasticity. More precisely we are concerned with a micro-macro model for rubber as the one proposed in [36]. Macroscopic quantities of interest such as the Piola-Kirchhoff stress tensor can be approximated for any value of the strain gradient by numerically solving a nonlinear PDE. This procedure is however computationally demanding. Hence, although conceptually satisfactory, this physically-based model is of no direct practical use. We aim to circumvent this difficulty by proposing a numerical strategy to reconstruct from in silico experiments an accurate analytical proxy for the micro-macro constitutive law.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

7.1.1. CIFRE convention

Participants: Céline Grandmont, Nicolas Pozin, Irène Vignon-Clementel.

CIFRE convention and contract with Air Liquide Santé International in the context of the ANRT on “Multiscale lung ventilation modeling in health and disease”, for the PhD thesis of Nicolas Pozin (March 2014 - February 2017).

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

8.1.1.1. ANR Project “EXIFSI”

Participants: Benoit Fabrèges, Miguel Ángel Fernández Varela [Principal Investigator], Mikel Landajuela Larma, Marina Vidrascu.

Period: 2012-2016
The aim of this project, coordinated by Miguel Ángel Fernández Varela, is to study mathematically and numerically new numerical methods for incompressible fluid-sructure interaction.

8.1.1.2. ANR Project “CARDIOXCOMP”

Participants: Muriel Boulakia, Damiano Lombardi, Jean-Frédéric Gerbeau [Principal Investigator], Fabien Raphel, Eliott Tixier.

Period: 2013-2013.
This project, coordinated by Jean-Frédéric Gerbeau, is carried out in the framework of a joint laboratory (“LabCom” call of ANR) with the software company NOTOCORD. The focus is the mathematical modeling of a device measuring the electrical activity of cardiomyocytes. The overall objective of CardioXcomp is to enrich NOTOCORD’s software with modelling and simulation solutions and provide to pharmacology research a completely new set incorporating state of the art signal processing and numerical simulation.

8.1.1.3. ANR Project “iFLOW”

Participants: Chloé Audebert, Jean-Frédéric Gerbeau, Irène Vignon-Clementel [co-Principal Investigator].

Period: 2013-2017.
This ANR-TecSan, co-managed by Eric Vibert (Paul Brousse Hospital) and Irene Vignon-Clementel, aims at developing an Intraoperative Fluorescent Liver Optimization Workflow to better understand the relationship between architecture, perfusion and function in hepatectomy.

Other partners: DHU Hepatinov - Hôpital Paul Brousse, Inria Mamba, Fluoptics, IfADo, MID.

8.1.1.4. Participation to other ANR projects

- Céline Grandmont is a member of the ANR TecSan Oxhelease
- Marina Vidrascu is a member of the ANR ARAMIS

8.1.2. Inria initiatives

8.1.2.1. ADT Project “MENAMES ”

Participants: Miguel Ángel Fernández Varela [Principal Investigator], Axel Fourmont, Marina Vidrascu.

Period: 2014-2016
The aim of this project, coordinated by Miguel Ángel Fernández Varela, is to implement in the FELiScE library several algorithms included in the shelddon library, in particular shell elements and domain decomposition methods.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. REVAMMAD

Participants: Matteo Aletti, Jean-Frédéric Gerbeau [correspondant], Damiano Lombardi.

Type: FP7-PEOPLE

Instrument: Marie Curie Initial Training Network

Duration: April 2013 - March 2017

Coordinator: Andrew Hunter, University of Lincoln (UK)

Partner: See the http://revammad.blogs.lincoln.ac.uk/partners/ web site

Inria contact: J-F Gerbeau

Abstract: http://revammad.blogs.lincoln.ac.uk REVAMMAD is a European Union project aimed at combatting some of the EU's most prevalent chronic medical conditions using retinal imaging. The project aims to train a new generation of interdisciplinary scientists for the academic, clinical and industrial sectors, and to trigger a new wave of biomedical interventions. The role of REO team within this consortium is to propose a mathematical model and a simulation tool for the retina hemodynamics.

8.3. International Initiatives

8.3.1. Inria International Labs

Participants: Céline Grandmont, Jessica Oakes, Irène Vignon-Clementel [correspondant].

Period: 2014-2015

Jessica Oakes was awarded an Inria@SiliconValley Grant for a post-doc at UC Berkeley to work on aerosol deposition in the lung.

8.3.2. Trans-Atlantic Network of Excellence for Cardiovascular Research

Participants: Grégory Arbia, Jean-Frédéric Gerbeau, Sanjay Pant, Irène Vignon-Clementel [correspondant].

Period: 2010-2015

This network, funded by the Leducq fondation, is working on the multi-scale modeling of single ventricle hearts for clinical decision support.

Other partners: see http://modelingventricle.clemson.edu/home.

8.3.3. German BMBF national project Lungsys II

Participant: Irène Vignon-Clementel.

Period: 2012-2015

"Systems Biology of Lung Cancer: Dynamic Properties of Early Spread and Therapeutic Options". In collaboration with Dirk Drasdo (EPI Mamba).

Other partners: see http://www.lungsys.de.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Stephanie Lindsey, PhD student at Cornell University (USA), Aug 2013 - February 2014 & 2 weeks in May 2014
- Weiguang Yang, Engineering research associate, Departments of Pediatrics and Cardiology, Stanford University (USA), May 20th-June 18th 2014
- Andrew Blaber, Carole Leguy, Joke Keijsers, Kouhyar Tavakolian, Simon Fraser University (Vancouver, Canada), May 26 - May 30, 2014

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

- Matteo Aletti
  - Co-organizer of the monthly Junior Seminar of Inria Paris-Rocquencourt
- Laurent Boudin
  - Co-organizer of the M2S2 workshop (Mathematical Models for Social Sciences), with J.-P. Nadal
- Miguel Ángel Fernández Varela
  - Organizer of the CEA-EDF-Inria summer school on Numerical methods for interface problems in fluid and solids with discontinuities, Cadarache, France (with P. Massin and J. Segré), 2014
  - Organizer of the International workshop on numerical methods and applications in fluid-structure interactions, November 24-25, 2014, Grenoble, France (co-organized with G.-H. Cottet, J-F. Gerbeau and E. Maitre)
- Jean-Frédéric Gerbeau
  - Organizer of the International workshop on numerical methods and applications in fluid-structure interactions, November 24-25, 2014, Grenoble, France (with G.-H. Cottet, M. Fernández and E. Maitre)
- Jessica Oakes
  - Assistant Organizer for the 4th International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease
  - Student Forum Leader: International Society of Aerosol Medicine
- Sanjay Pant
  - Co-organizer of the 4th International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, May 21rst-22nd, Rocquencourt, France
- Elisa Schenone
  - Co-organizer of the monthly Junior Seminar of Inria Paris-Rocquencourt
- I. Vignon-Clementel
  - Organizer of the monthly seminar at Inria Paris-Rocquencourt on “modeling and scientific computing”

  - Organizer of the 4th International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, May 21rst-22nd, Rocquencourt, France. This event was coorganized with the School of Medicine, Stanford University & REO. It was a great success! Over 70 participants came from all over the world, from the USA and France, but also from as far as Japan, Turkey or Australia. Participants particularly liked the mixture of mathematics/engineering and clinical research presented in an understandable way for both communities. This fostered lively discussions after talks and at the poster session. Three young investigators received awards from the *Fondation Sciences Mathématiques de Paris*; one of them is Stephanie Lindsey, a visiting PhD student at REO from Cornell University. http://www.rocq.inria.fr/engfrontiersped
  - Organizer of the 5th general meeting of the Transatlantic Network of Excellence for Cardiovascular Research MOCHA, May 22nd-24th, Rocquencourt, France.

9.1.2. Journal editorial boards

- Jean-Frédéric Gerbeau
  - Editor-in-Chief of Mathematical Modelling and Numerical Analysis (M2AN).
  - Member of the editorial board of International Journal for Numerical Methods in Biomedical Engineering (IJNMBE).
  - Member of the editorial board of Communications in Applied and Industrial Mathematics.
- I. Vignon-Clementel
  - Review Editor of Frontiers in Pediatric Cardiology.

9.1.3. Conferences

- Chloé Audebert
  - Minisymposium talk, 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona, Spain.
  - PhD students seminar, Université Paris-Decartes, February 20th, 2014, Paris, France
  - Poster session, 4th International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, Inria Paris-Rocquencourt, May 21-22, 2014, Paris, France
- Laurent Boudin
  - Invited speaker at Workshop "PDE models in social sciences", closure of Peter Markowich's chair at FSMP, Paris, France, January 2014.
  - Seminar, Numerical analysis and PDEs, LMPP, Univ. Lille 1, France, March 2014.
  - Seminar, Applied Mathematics, IMB, Univ. Bordeaux, France, March 2014.
  - Seminar, Mathematics and applications, Irmar, ENS Rennes, France, April 2014.
  - Invited speaker at Conference "Problems on kinetic theory and PDEs", Univ. Novi Sad, Serbia, September 2014.
  - Invited speaker at Workshop "Kinetic models for complex gases", Univ. Bordeaux, France, October 2014.
- Muriel Boulakia
  - Contributed talk, Hybrid Inverse Problems, Paris, February 2014
  - Contributed talk, LJLL-Shangaï Meeting, Paris, July 2014
  - Contributed talk, GDR Metice workshop, Paris, November 2014
- Miguel Ángel Fernández Varela
  - Invited plenary lecture, 12th Franco-Romanian conference on applied mathematics, Lyon (France) August 2014.

  - Minisymposium talk, 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona, Spain.
  - Seminar, University of Caen, October, 2014, France
- Benoit Fabrèges
  - Minisymposium talk, 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona, Spain.
  - Contributed talk, International workshop on numerical methods and applications in fluid-structure interactions, November 24-25, Grenoble, France, 2014.
- Justine Fouchet-Incaux
  - Contributed talk, CANUM, Carry-le-Rouet, France, April 2014.
  - Poster, IXème congrès de Physiologie, de Pharmacologie et de Thérapeutique, Poitiers, April 2014.
- Jean-Frédéric Gerbeau
  - Invited plenary lecture, ESCO 2014, Pilsen (Czech Republic), June 2014
  - Invited plenary lecture, CARI 2014, Saint-Louis (Senegal), October 2014
  - Invited lecture, International Symposium Modeling and Simulation of the Cardiovascular System, Heidelberg (Germany), February 2014
  - Invited seminar, Collège de France, June 2014
  - Invited lecture, Workshop GDR Mecabio, Paris, 2014
  - Invited lecture, Workshop on Model Order Reduction and Data, Paris, 2014
  - Minisymposium talk, 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona, Spain.
  - Minisymposium talk, 7th World Congress of Biomechanics (WCB), July 6-11, 2014, Boston, USA.
- Céline Grandmont
  - Seminar, Nancy Univ., april 2014.
  - Invited speaker, PhD student day, sept. 2014.
- Mikel Landajuela
  - Minisymposium talk, 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona, Spain.
  - Seminar, UCL/Inria Workshop on embedded interfaces, London, UK, February 25-26, 2014
  - Poster, International workshop on numerical methods and applications in fluid-structure interactions, Grenoble, France, November 24–25, 2014;
- Damiano Lombardi
  - Seminar scientific computing , IMB Bordeaux, september 25
  - GDR Metice, Paris, 19-11-2014,
  - International Workshop on Fluid Structure Interaction, 24 novembre 2014, Grenoble
- Jessica Oakes
  - Invited Seminar Talk at Technion - Israel Institute of Technology, Haifa Israel July 2014.
  - Seminar Talk at University of California Berkeley, Berkeley California USA, September 2014
  - Seminar Talk at Inria@SiliconValley Workshop, Paris France July 2014.

  - Poster and Podium Talk at the International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease. May 2014, Paris France.
  - Podium Talk at Second Aerosol Dosimetry Conference, October 2014. Irvine, California, USA.
  - Podium Talk at American Physics Society, Division of Fluid Dynamics, November 2014. San Francisco, California, USA
- Stephanie Lindsey
  - Contributed talk at "American Physical Society Division of Fluid Dynamics 67th Annual Meeting", November 23-25, 2014 San Francisco, California
  - Invited speaker, "4th International Conference on Engineering Frontiers in Pediatric and Congenital Heart", May 21-22, 2014 Paris, France
  - Invited speaker, Junior Seminar, Inria, January 22, 2014 Paris, France.
- Sanjay Pant
  - Contributed talk, Mathematics and Biology: 2nd Young Investigators International Workshop, Paris, France, April 3-4, 2014.
  - Poster, 4th International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, Paris, France, May 21-22, 2014.
  - Contributed talk, 5th Annual Meeting of the Leducq Foundation Network of Excellence in Modeling of Single Ventricle Hearts Inria, Paris-Rocquencourt, France, May 22-24, 2014.
  - Minisymposium talk, 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona, Spain.
- Elisa Schenone
  - Poster, 4th International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, Paris, May 21-22 201
  - Seminar, Inria-Rocquencourt Junior Seminar, Paris, June 17th 2014
  - Seminar, PhD students working group of Jacques-Louis Lions Laboratory of UPMC, Paris, March 21st 2014
- Marc Thiriet
  - Invited Speaker, CASTS-LJLL Workshop on Applied Mathematics and Mathematical Sciences. National Taiwan University, May 26 - 29, 2014
  - Keynote speaker, CompIMAGE'14, Sept. 3-5, Pittsburgh, USA
  - Invited Speaker, International Conference on Progress in Fluid Dynamics and Simulation, National Taiwan University, October 25-27, 2014
  - Miraucourt O, Génevaux O, Szopos M, Thiriet M, Talbot H, Salmon S, Passat N. s. 2014 IEEE International Symposium on Biomedical Imaging, Beijing, China, April 29 - May 2, 2014
  - M Thiriet, M Solovchuk, TWH Sheu, HIFU , CompIMAGE'14, Sept. 3-5, Pittsburgh, USA
  - Solovchuk M, Sheu TWH, Thiriet M, 1st Global Conference on Biomedical Engineering (GCBME 2014) and 9th Asian Pacific Conference on Medical and Biological Engineering (APCMBE 2014), Oct. 9-12, 2014, NCKU, Tainan **Young Investigator award**
  - Solovchuk M, Sheu TWH, Thiriet M,, International Conference on Progress in Fluid Dynamics and Simulation, National Taiwan University October 25–27, 2014
- Marina Vidrascu
  - Modeling and scientific computing seminar at Inria Paris-Rocquencourt on January 7th, 2014.

  - Minisymposium talk, 11th World Congress on Computational Mechanics (WCCM XI), July 20-25, 2014, Barcelona, Spain.
  - Seminar at Univ Compiègne, October 7th, 2014.
- Irène Vignon-Clementel
  - Invited talk, Navier-Stokes workshop “une equation lumineuse” , Ecole Polytechnique, March 12th, Palaiseau, France.
  - Invited talk, Institute of Child Health, University College London, April 3rd, London, UK.
  - Invited talk, Notocord workshop, Inria Paris-Rocquencourt, June 6th, 2014, France.
  - Talk, Inria-Dassault System meeting, Oct. 29th, 2014, Paris, France .

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

DUT :

- Justine Fouchet-Incaux 1ère année: Mathématiques S1, 28h, IUT d’Orsay, département Mesures Physiques, Université Paris-Sud,
- Justine Fouchet-Incaux 2ème année: Mathématiques S4, 33h, IUT d’Orsay, département Mesures Physiques, Université Paris-Sud

Licence :

- Chloé Audebert
  - "Calculus" (72h), L1 - undergraduate, Université Paris 6 UPMC, France (1rst semester 2014-2015).
  - Numerical ressources for Small Private Online Classes (SPOC), L1 - undergraduate, Université Paris 6 UPMC, France.
- Laurent Boudin
  - Multivariable calculus and multiple integrals (114 h), L2, UPMC.
  - Shared studies supervision in mathematics licence for approximately 500 students (30h), L2-L3, UPMC.
- Muriel Boulakia
  - Scilab (35h), L2, UPMC
  - Hilbertian analysis (45h), L3, Polytech’Paris,
- Miguel Ángel Fernández Varela
  - Scientific computing, 30h, L3, École des Ponts ParisTech,
- Céline Grandmont
  - Numerical Analysis, 36 h, L3, UPMC
  - EDO, 24 h, L3, UPMC
- Damiano Lombardi
  - Linear Algebra TD, 32h, L1 Physique-Chimie, UP-SUD
- Irène Vignon-Clementel
  - Mathematics for biology, 64h ETD, L1 - undergraduate, Univ. de Versailles Saint Quentin

Master :

- Laurent Boudin
  - Basics for numerical methods (72h), M1, UPMC.

  - Studies supervision in mathematics master for 15 students (20h), M1, UPMC.
- Muriel Boulakia
  - Preparatory course for teaching admission examination Agrégation (60h), M2, UPMC,
- Jean-Frédéric Gerbeau
  - Numerical methods in hemodynamics (20h), M2, UPMC / Univ Paris-Sud / Ecole Polytechnique.
- Miguel Ángel Fernández Varela
  - Numerical methods in bio-fluids, 6h, M2, University of Vigo, Spain.
- Damiano Lombardi
  - Numerical Methods, 48h, Paris Polytech, M1 Robotique

Engineering schools:

- Irène Vignon-Clementel. Numerical simulations of blood flow, 1h30, as part of the undergraduate "continuum mechanics" class at AgroParisTech, France

9.2.2. Supervision

PhD: Grégory Arbia, *Multi-scale Modeling of Single Ventricle Hearts for Clinical Decision Support*, Univ Paris 6 UPMC, defended December 16, 2014. Supervisors: J-F. Gerbeau & I. Vignon-Clementel, [13].

PhD: Jimmy Mullaert, *Fluid-structure interaction*, Univ Paris 6 UPMC, defended on December 17 . Supervisors: M.A. Fernández Varela& Y. Maday, [14].

PhD: Elisa Schenone, *Inverse problems in electrocardiology*, Univ Paris 6 UPMC, defended on November 28. Supervisors: J-F. Gerbeau & M. Boulakia, [15].

PhD: Saverio Smaldone, *Numerical methods for cardiac hemodynamics*, Univ Paris 6 UPMC, defended on October 13, Supervisors: J-F. Gerbeau & M.A. Fernández Varela, [16].

PhD in progress: Chloé Audebert, *Modeling of liver hemodynamics*, since October 2013. Supervisors: J-F. Gerbeau & I. Vignon-Clementel.

PhD in progress: Justine Fouchet-Incaux, *Mathematical and numerical modeling of the human breathing*, since October 2011. Supervisors: C. Grandmont & B. Maury.

PhD in progress: Mikel Landajuela, *Coupling schemes and unfitted mesh methods for fluid-structure interaction*, since October 2012, Supervisor: M.A. Fernández Varela.

PhD in progress: Matteo Aletti, *Multiscale retinal vascular modeling* , since January 2014 Supervisors: J-F. Gerbeau & Damiano Lombardi.

PhD in progress: Eliott Tixier, *Stem cells electrophysiology*, since September 2014 2014. Supervisors: J-F. Gerbeau & Damiano Lombardi.

PhD in progress: Nicolas Pozin *Multiscale lung ventilation modeling in health and disease*, since March 2014. Supervisors: C. Grandmont & I. Vignon-Clementel.

PhD in progress: Stéphane Liwarek, *Air flow in the nasal cavity*, October 2010-September 2014. Supervisors: M.A. Fernández Varela & J-F. Gerbeau.

9.2.3. Juries and hiring committees

- Laurent Boudin
  - Member of the PhD committees of Galina Vinogradova (SciencesPo, december 2014)
- Muriel Boulakia
  - Hiring committee: UPMC and Univ. Paris-Diderot
- Jean-Frédéric Gerbeau

  - PhD committees: Guilhem Lepoultier, Univ. Orsay (referee), Liesbeth Taelman, Univ. Gand, Belgique (referee), Adela Puscas, Univ. Paris-Est (referee), Christophe Chnafa, Univ. Montpellier 2 (referee), Agnès Leroy, Univ. Paris-Est. (member)
  - Hiring committee: Univ Orsay, CR2 Inria Paris-Rocquencourt, CR1 Inria.
- Céline Grandmont
  - Hiring committee: Lyon Univ. (Assitant Professor position).
  - Head habilitation (HDR) committee: B. Mauroy, Nice univ.
- Marina Vidrascu
  - Member of the Hiring committee Perpignan (professor)
  - Member of the PhD committee of Claire Dupont and Jimmy Mullaert
- Irène Vignon-Clementel
  - Member of the PhD committee of Xiaofei Wang, UPMC, Oct. 17th
  - PhD referee of Alessia Baretta, LaBS, Politecnico di Milano, Italy, Oct 21rst.
  - Member of the PhD committee of Grégory Arbia, UPMC, Dec 16th.

9.3. Service activities

- Laurent Boudin
  - Member of the Board of Mathematics Licence (EFU de Licence de mathématiques), UPMC.
  - Member of the think-tank for third-year programs in Mathematics at UPMC.
  - Member of the IREM (Institutes for Research on Mathematics Teaching) Scientific Committee.
- Muriel Boulakia
  - Supervisor of the teaching of mathematics at the engineer school Polytech Paris-UPMC
- Jean-Frédéric Gerbeau
  - Service activity at Inria: Délégué Scientifique / Chairman of the project-teams' committee of Inria Paris-Rocquencourt research center; Member of the Inria Evaluation Committee; Member of the Inria International Chairs committee.
  - Service activity in other French institutions: member of the research committee of Sorbonne Universités; member of the scientific committee of the Faculty of Science, University Versailles Saint-Quentin; member of the scientific committee of Labex NUMEV, Montpellier.
  - Service activity abroad: member of the Reference Committee of the PhD program Mathematical Models and Methods in Engineering (Politecnico di Milano, Italy);
- Céline Grandmont
  - Member of the CNU 26 (2011–2015). Member of the CNU extended board.
- Marc Thiriet
  - President of thematic comittee CT3 (Biomedical Simulation and Applications to Health) of GENCI (Grand Equipement National de Calcul Intensif – National Large Equipement for Intensive Computation).
  - Member of Evaluation Groups of the Canadian Granting Agency NSERC 1501 (Genes, Cells and Molecules), 1502 (Biological Systems and Functions), 1504 (Chemistry), 1507 (Computer Science), 1508 (Mathematics and Statistics), 1511 (Materials and Chemical Eng.), and mainly 1512 (Mechanical Eng., both Solids and Fluids sections).
  - Member of Scientific Council of DiscInNet

- Marina Vidrascu
  - Member of the post-docs selection committee, Inria Paris-Rocquencourt
- Irène Vignon-Clementel
  - Member of the PhD grant committee, Inria Paris-Rocquencourt
  - Mediator between PhD students and their supervisors for Inria Paris-Rocquencourt

9.4. Popularization

- Matteo Aletti
  - presentation at "Incontro Neo-Laureati" (Conférance jeunes diplômes) at Politecnico di Milano
  - presentation about REVAMMAD project at ArtVerona
- Céline Grandmont
  - Popularization paper "Inspiration mathématique: la modélisation du poumon", in Mathématique l'explosion continue, edited by SFdS, SMAI, SMF.
  - Conference «Nuit des Sciences, ébulition», ENS Paris, june 2014
  - Conference «Mathematic Park a Bobigny», 300 students (high school level), oct. 2014
  - Conference «Filles et Maths: une equation lumineuse», 60 students, (high school level), oct. 2014.
- Irene Vignon-Clementel
  - Conference in High School Blanche de Castille, March 25th, Le Chesnay

10. Bibliography

Major publications by the team in recent years

[1] L. Boudin, L. Desvillettes, R. Motte. *A modeling of compressible droplets in a fluid*, in "Commun. Math. Sci.", 2003, vol. 1, n° 4, pp. 657–669

[2] M. Boulakia, S. Guerrero. *Regular solutions of a problem coupling a compressible fluid and an elastic structure*, in "Journal de Mathématiques Pures et Appliquées", 2010, vol. 94, n° 4, pp. 341-365 [*DOI :* 10.1016/j.matpur.2010.04.002], http://hal.inria.fr/hal-00648710/en/

[3] E. Burman, M. A. Fernández. *Galerkin Finite Element Methods with Symmetric Pressure Stabilization for the Transient Stokes Equations: Stability and Convergence Analysis*, in "SIAM Journal on Numerical Analysis", 2008, vol. 47, n° 1, pp. 409–439

[4] E. Burman, M. A. Fernández. *Stabilization of explicit coupling in fluid-structure interaction involving fluid incompressibility*, in "Comput. Methods Appl. Mech. Engrg.", 2008

[5] P. Causin, J.-F. Gerbeau, F. Nobile. *Added-mass effect in the design of partitioned algorithms for fluid-structure problems*, in "Comp. Meth. Appl. Mech. Engng.", 2005, vol. 194, n° 42-44

[6] J.-J. Christophe, T. Ishikawa, N. Matsuki, Y. Imai, K. Takase, M. Thiriet, T. Yamaguchi. *Patient-specific morphological and blood flow analysis of pulmonary artery in the case of severe deformations of the lung due to pneumothorax*, in "Journal of Biomechanical Science and Engineering", 2010, vol. 5, n° 5, pp. 485-498, http://hal.inria.fr/inria-00543090

[7] M. A. FERNÁNDEZ, J.-F. GERBEAU, C. GRANDMONT. *A projection semi-implicit scheme for the coupling of an elastic structure with an incompressible fluid*, in "Internat. J. Numer. Methods Engrg.", 2007, vol. 69, n^{o} 4, pp. 794–821

[8] C. FETITA, S. MANCINI, D. PERCHET, F. PRÊTEUX, M. THIRIET, L. VIAL. *Computational model of oscillatory flow in the proximal part of tracheobronchial trees*, in "Computer Methods in Biomechanics and Biomedical Engineering", 2005, vol. 8, pp. 279-293

[9] C. GRANDMONT. *Existence of weak solutions for the unsteady interaction of a viscous fluid with an elastic plate*, in "SIAM J. Math. Anal.", 2008, vol. 40, n^{o} 2, pp. 716–737

[10] P. MOIREAU, C. BERTOGLIO, N. XIAO, C. A. FIGUEROA, C. A. TAYLOR, D. CHAPELLE, J.-F. GERBEAU. *Sequential identification of boundary support parameters in a fluid-structure vascular model using patient image data*, in "Biomechanics and Modeling in Mechanobiology", July 2012, vol. 12, n^{o} 3, pp. 475-496 [*DOI :* 10.1007/S10237-012-0418-3], https://hal.inria.fr/hal-00760703

[11] M. THIRIET. *Biology and Mechanics of Blood Flows, part I: Biology of Blood Flows (652 p.), part II: Mechanics and Medical Aspects of Blood Flows (464 p.)*, CRM Series in Mathematical Physics, Springer, 2008

[12] I. VIGNON-CLEMENTEL, C. A. FIGUEROA, K. E. JANSEN, C. A. TAYLOR. *Outflow Boundary Conditions for Three-dimensional Finite Element Modeling of Blood Flow and Pressure in Arteries*, in "Computer Methods in Applied Mechanics and Engineering", 2006, vol. 195, pp. 3776-3796

Publications of the year

Doctoral Dissertations and Habilitation Theses

[13] G. ARBIA. *Multiscale modeling of blood flow in the context of congenital heart disease*, Université Pierre et Marie Curie, December 2014, https://tel.archives-ouvertes.fr/tel-01099605

[14] J. MULLAERT. *Numerical methods for incompressible fluid-structure interaction*, Université Pierre et Marie Curie, December 2014, https://hal.inria.fr/tel-01105257

[15] E. SCHENONE. *Reduced Order Models, Forward and Inverse Problems in Cardiac Electrophysiology*, Université Pierre et Marie Curie - Paris VI, November 2014, https://tel.archives-ouvertes.fr/tel-01092945

[16] S. SMALDONE. *Numerical analysis and simulations of coupled problems for the cardiovascular system*, Université Pierre et Marie Curie (Paris 6), October 2014, https://tel.archives-ouvertes.fr/tel-01076506

Articles in International Peer-Reviewed Journals

[17] G. ARBIA, C. CORSINI, C. BAKER, G. PENNATI, T.-Y. HSIA, I. VIGNON-CLEMENTEL. *Pulmonary hemodynamics simulations before stage 2 single ventricle surgery: patient-specific parameter identification and clinical data assessment*, in "Cardiovascular Engineering and Technolodgy", 2015, 18 p. [*DOI :* 10.1007/S13239-015-0212-3], https://hal.inria.fr/hal-01063967

[18] G. ARBIA, C. CORSINI, M. E. MOGHADAM, A. MARSDEN, F. MIGLIAVACCA, G. PENNATI, T.-Y. HSIA, I. VIGNON-CLEMENTEL. *Numerical blood flow simulation in surgical corrections: what do we need*

for an accurate analysis ?, in "Journal of Surgical Research", January 2014, vol. 186, n$^{\text{o}}$ 1, pp. 44-55 [*DOI :* 10.1016/J.JSS.2013.07.037], https://hal.inria.fr/hal-00911298

[19] C. BERTOGLIO, D. BARBER, N. GADDUM, I. VALVERDE, M. RUTTEN, P. BEERBAUM, P. MOIREAU, R. HOSE, J.-F. GERBEAU. *Identification of artery wall stiffness: in vitro validation and in vivo results of a data assimilation procedure applied to a 3D fluid-structure interaction model*, in "Journal of Biomechanics", March 2014, vol. 47, n$^{\text{o}}$ 5, pp. 1027–1034 [*DOI :* 10.1016/J.JBIOMECH.2013.12.029], https://hal.inria.fr/hal-00925902

[20] L. BOUDIN, B. GREC, F. SALVARANI. *The Maxwell-Stefan diffusion limit for a kinetic model of mixtures*, in "Acta Applicandae Mathematicae", 2014, pp. 1-12 [*DOI :* 10.1007/S10440-014-9886-Z], https://hal.archives-ouvertes.fr/hal-00554744

[21] M. BOULAKIA, A. GENADOT, M. THIEULLEN. *Simulation of SPDE's for Excitable Media using Finite Elements*, in "Journal of Scientific Computing", November 2014, 25 p. , http://hal.upmc.fr/hal-01078727

[22] E. BURMAN, M. A. FERNÁNDEZ. *An unfitted Nitsche method for incompressible fluid-structure interaction using overlapping meshes*, in "Computer Methods in Applied Mechanics and Engineering", July 2014, vol. 279, pp. 497-514 [*DOI :* 10.1016/J.CMA.2014.07.007], https://hal.inria.fr/hal-00918272

[23] E. BURMAN, M. A. FERNÁNDEZ. *Explicit strategies for incompressible fluid-structure interaction problems: Nitsche type mortaring versus Robin-Robin coupling*, in "International Journal for Numerical Methods in Engineering", 2014, vol. 97, n$^{\text{o}}$ 10, pp. 739–758 [*DOI :* 10.1002/NME.4607], https://hal.inria.fr/hal-00819948

[24] C. CORRADO, J.-F. GERBEAU, P. MOIREAU. *Identification of weakly coupled multiphysics problems. Application to the inverse problem of electrocardiography*, in "Journal of Computational Physics", February 2015, vol. 283, pp. 271–298 [*DOI :* 10.1016/J.JCP.2014.11.041], https://hal.inria.fr/hal-01091751

[25] C. CORSINI, C. BAKER, A. BARETTA, G. BIGLINO, A. M. HLAVACEK, T.-Y. HSIA, E. KUNG, A. MARSDEN, F. MIGLIAVACCA, I. VIGNON-CLEMENTEL, G. PENNATI. *Integration of Clinical Data Collected at Different Times for Virtual Surgery in Single Ventricle Patients: A Case Study*, in "Annals of Biomedical Engineering", October 2014, 11 p. , https://hal.inria.fr/hal-01097802

[26] C. DARQUENNE, M. G. BORJA, J. M. OAKES, E. C. BREEN, M. OLFERT, M. SCADENG, G. K. PRISK. *Increase in relative deposition of fine particles in the rat lung periphery in the absence of gravity*, in "Journal of Applied Physiology", August 2014, pp. 880-886, https://hal.inria.fr/hal-01100097

[27] L. DESVILLETTES, T. LEPOUTRE, A. MOUSSA. *Entropy, Duality and Cross Diffusion*, in "SIAM Journal on Mathematical Analysis", 2014, vol. 46, n$^{\text{o}}$ 1, https://hal.inria.fr/hal-00785379

[28] A.-C. EGLOFFE, A. GLORIA, J.-C. MOURRAT, T. N. NGUYEN. *Random walk in random environment, corrector equation and homogenized coefficients: from theory to numerics, back and forth*, in "IMA Journal of Numerical Analysis", 2014, 44 p. [*DOI :* 10.1093/IMANUM/DRU010], https://hal.inria.fr/hal-00749667

[29] M. A. FERNÁNDEZ, J.-F. GERBEAU, S. SMALDONE. *Explicit coupling schemes for a fluid-fluid interaction problem arising in hemodynamics*, in "SIAM Journal on Scientific Computing", July 2014, vol. 36, n$^{\text{o}}$ 6, pp. 2557-2583 [*DOI :* 10.1137/130948653], https://hal.inria.fr/hal-00915213

[30] M. A. FERNÁNDEZ, J. MULLAERT, M. VIDRASCU. *Generalized Robin-Neumann explicit coupling schemes for incompressible fluid-structure interaction: stability analysis and numerics*, in "International Journal for Numerical Methods in Engineering", January 2015, vol. 101, n° 3, pp. 199-229 [*DOI :* 10.1002/NME.4785], https://hal.inria.fr/hal-00875819

[31] J. FOUCHET-INCAUX. *Artificial boundaries and formulations for the incompressible Navier-Stokes equations. Applications to air and blood flows*, in "SeMa Journal", 2014, 40 p. [*DOI :* 10.1007/S40324-014-0012-Y], https://hal.inria.fr/hal-00926273

[32] J.-F. GERBEAU, D. LOMBARDI. *Approximated Lax Pairs for the Reduced Order Integration of Nonlinear Evolution Equations*, in "Journal of Computational Physics", May 2014, vol. 265, pp. 246-269 [*DOI :* 10.1016/J.JCP.2014.01.047], https://hal.inria.fr/hal-00933172

[33] J.-F. GERBEAU, D. LOMBARDI, E. SCHENONE. *Reduced order model in cardiac electrophysiology with approximated Lax pairs*, in "Advances in Computational Mathematics", October 2014, 28 p. [*DOI :* 10.1007], https://hal.inria.fr/hal-01093488

[34] G. GEYMONAT, S. HENDILI, F. KRASUCKI, M. VIDRASCU. *Matched asymptotic expansion method for an homogenized interface model*, in "M3AS", March 2014, vol. 24, n° 3, pp. 573-597 [*DOI :* 10.1142/S0218202513500607.], https://hal.archives-ouvertes.fr/hal-00757005

[35] G. GEYMONAT, S. HENDILI, F. KRASUCKI, M. VIDRASCU. *Numerical validation of an Homogenized Interface Model*, in "Computer Methods in Applied Mechanics and Engineering", 2014, vol. 269, pp. 356-380 [*DOI :* 10.1016/J.CMA.2013.11.009], https://hal.inria.fr/hal-00839616

[36] A. GLORIA, P. LE TALLEC, M. VIDRASCU. *Foundation, analysis, and numerical investigation of a variational network-based model for rubber*, in "Continuum Mechanics and Thermodynamics", 2014, vol. 26, n° 1, pp. 1–31 [*DOI :* 10.1007/S00161-012-0281-6], https://hal.archives-ouvertes.fr/hal-00673406

[37] A. IOLLO, D. LOMBARDI. *Advection modes by optimal mass transfer*, in "Physical Review E", 2014, vol. 89, 022923 [*DOI :* 10.1103/PHYSREVE.89.022923], https://hal.archives-ouvertes.fr/hal-00992346

[38] J. M. OAKES, E. C. BREEN, M. SCADENG, G. S. TCHANTCHOU, C. DARQUENNE. *MRI-Based Measurements of Aerosol Deposition in the Lung of Healthy and Elastase-Treated Rats*, in "Journal of Applied Physiology", May 2014, vol. 116, pp. 1561-1568 [*DOI :* 10.1152/JAPPLPHYSIOL.01165.2013], https://hal.inria.fr/hal-01095643

[39] J. OAKES, A. L. MARSDEN, C. GRANDMONT, S. C. SHADDEN, C. DARQUENNE, I. VIGNON-CLEMENTEL. *Airflow and Particle Deposition Simulations in Health and Emphysema: From In Vivo to In Silico Animal Experiments*, in "Annals of Biomedical Engineering", April 2014, vol. 42, n° 4, pp. 899-914 [*DOI :* 10.1007/S10439-013-0954-8], https://hal.archives-ouvertes.fr/hal-00916348

[40] S. PANT, B. FABRÈGES, J.-F. GERBEAU, I. VIGNON-CLEMENTEL. *A methodological paradigm for patient-specific multi-scale CFD simulations: from clinical measurements to parameter estimates for individual analysis*, in "International Journal for Numerical Methods in Biomedical Engineering", December 2014, vol. 30, n° 12, pp. 1614–1648 [*DOI :* 10.1002/CNM.2692], https://hal.inria.fr/hal-01093879

[41] C. TOUZÉ, M. VIDRASCU, D. CHAPELLE. *Direct finite element computation of non-linear modal coupling coefficients for reduced-order shell models*, in "Computational Mechanics", 2014, vol. 54, pp. 567-580 [*DOI :* 10.1007/s00466-014-1006-4], https://hal.inria.fr/hal-00955582

Invited Conferences

[42] M. A. FERNÁNDEZ, M. LANDAJUELA, J. MULLAERT, M. VIDRASCU. *Robin-Neumann schemes for incompressible fluid-structure interaction*, in "Domain Decomposition Methods in Science and Engineering XXII", Lugano, Switzerland, Lecture Notes in Computer Science (LNCS), Springer, 2015, https://hal.inria.fr/hal-01113088

International Conferences with Proceedings

[43] J. FOUCHET-INCAUX, C. GRANDMONT, S. MARTIN, B. MAURY. *Modeling of flow limitation phenomena in the human respiratory tract during forced expiration*, in "18th Annual Meeting of French Society of Pharmacology and Therapeutics, 81th Annual Meeting of Society of Physiology, 35th Pharmacovigilance Meeting, 15th APNET Seminar, 12th CHU CIC Meeting and 9th Annual Meeting of Physiology, Pharmacology and Therapeutics", Poitier, France, WILEY-BLACKWELL, April 2014, vol. 28, https://hal.inria.fr/hal-01095925

[44] J. OAKES, C. GRANDMONT, S. C. SHADDEN, I. VIGNON-CLEMENTEL. *Development of a 3D to 1D Particle Transport Model to Predict Deposition in the Lungs*, in "67th Annual Meeting of the APS Division of Fluid Dynamics", San Francisco, United States, Bulletin of the American Physical Society, APS, November 2014, vol. 59, n^o 20, https://hal.inria.fr/hal-01099800

Scientific Books (or Scientific Book chapters)

[45] C. GRANDMONT, S. NECASOVÁ, M. LUKACOVA-MEDVID'OVA. *Mathematical and Numerical Analysis of some fluid-structure interaction problems*, in "Fluid-Structure interaction and biomedical applications", T. BODNÁR, G. P. GALDI, Š. NEČASOVÁ (editors), Advances in Mathematical Fluid Mechanics, Springer, 2014, https://hal.inria.fr/hal-00917363

[46] M. THIRIET. *Anatomy and Physiology of the Circulatory and Ventilatory Systems*, Biomathematical and Biomechanical Modeling of the Circulatory and Ventilatory Systems, Springer, New York, 2014, vol. 6, 585 p. , https://hal.inria.fr/hal-00922907

Research Reports

[47] M. A. FERNÁNDEZ, M. LANDAJUELA, M. VIDRASCU. *Fully decoupled time-marching schemes for incompressible fluid/thin-walled structure interaction*, Inria, December 2014, n^o RR-8425, https://hal.inria.fr/hal-00918498

[48] M. A. FERNÁNDEZ, J. MULLAERT. *Convergence analysis for a class of splitting schemes in incompressible fluid-structure interaction*, Inria, January 2015, n^o RR-8670, https://hal.inria.fr/hal-01102975

Other Publications

[49] L. BOUDIN, C. GRANDMONT, A. LORZ, A. MOUSSA. *Modelling and numerics for respiratory aerosols*, July 2014, https://hal.archives-ouvertes.fr/hal-01044590

[50] L. BOUDIN, F. SALVARANI. *Opinion Dynamics : Kinetic Modelling with Mass Media, Application to the Scottish Independence Referendum*, February 2015, https://hal.archives-ouvertes.fr/hal-01114091

[51] M. BOULAKIA. *Quantification of the unique continuation property for the nonstationary Stokes problem*, December 2014, https://hal.inria.fr/hal-01094490

[52] P. CAZEAUX, C. GRANDMONT, Y. MADAY. *Homogenization of a model for the propagation of sound in the lungs*, June 2014 [*DOI :* 10.1137/130916576], http://hal.upmc.fr/hal-00764982

[53] M. DE BUHAN, A. GLORIA, P. LE TALLEC, M. VIDRASCU. *Reconstruction of a constitutive law for rubber from in silico experiments using Ogden's laws*, January 2014, https://hal.inria.fr/hal-00933240

[54] M. A. FERNÁNDEZ, M. LANDAJUELA. *Splitting schemes for incompressible fluid/thin-walled structure interaction with unfitted meshes*, September 2014, https://hal.inria.fr/hal-01095634

[55] J. FOUCHET-INCAUX, C. GRANDMONT, S. MARTIN. *Numerical stability of a multi-dimensional modelling of 3D/0D airflows and blood flows*, December 2014, https://hal.inria.fr/hal-01095960

[56] A. MOUSSA. *Some variants of the classical Aubin-Lions Lemma*, January 2014, https://hal.archives-ouvertes.fr/hal-00938186

[57] S. PANT, D. LOMBARDI. *An information-theoretic approach to assess practical identifiability of parametric dynamical systems*, January 2015, https://hal.inria.fr/hal-01099901

References in notes

[58] A. AMSDEN, P. O'ROURKE, T. BUTLER. *A computer program for chemically reactive flows with sprays*, Los Alamos National Laboratory, 1989, n^o LA-11560-MS

[59] M. A. BIOT. *Theory of propagation of elastic waves in a fluid-saturated porous solid. II higher frequency range*, in "J. Acoust. Soc. Am.", 1956, vol. 28, pp. 179–191

[60] D. CHAPELLE, J. SAINTE-MARIE, J.-F. GERBEAU, I. VIGNON-CLEMENTEL. *A poroelastic model valid in large strains with applications to perfusion in cardiac modeling*, in "Computational Mechanics", 2010, vol. 46, n^o 1, pp. 91-101 [*DOI :* 10.1007/s00466-009-0452-x]

[61] J. DUPAYS, Y. FABIGNON, P. VILLEDIEU, G. LAVERGNE, G. ESTIVALEZES. *Some aspects of two phase flows in solid propellant rocket motors, in Solid propellant chemistry, combustion and interior ballistics*, in "Progress in Astronautics and Aeronautics", V. YANG, T. BRILL, W. PEN (editors), Academic Press, 2000, vol. 185

[62] G. LINES, P. GROTTUM, A. TVEITO. *Modeling the electrical activity of the heart. A bidomain model of the ventricles embedded in a torso*, in "Comput. Visual. Sci.", 2003, vol. 5, pp. 195-213

[63] R. MOTTE. *A numerical method for solving particle-fluid equations*, in "Trends in numerical and physical modeling for industrial multiphase flows", Cargèse, France, 2000

[64] A. QUARTERONI, S. RAGNI, A. VENEZIANI. *Coupling between lumped and distributed models for blood flow problems*, in "Comput. Visual Sci.", 2001, vol. 4, pp. 111–124

[65] F. SACHSE. *Computational Cardiology: Modeling of Anatomy, Electrophysiology, and Mechanics*, Springer-Verlag, 2004

[66] J. SUNDNES, G. LINES, X. CAI, B. NIELSEN, K.-A. MARDAL, A. TVEITO. *Computing the electrical activity in the heart*, Springer-Verlag, 2006

[67] K. TERZAGHI. *Theoretical Soil Mechanics*, John Wiley and SonsNew-York, 1943

[68] F. WILLIAMS. *Combustion theory*, 2nd, Benjamin Cummings, 1985