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ACTIVITY REPORT

Project-Team

COMMEDIA

Computational mathematics for bio-medical applications

IN COLLABORATION WITH: Laboratoire Jacques-Louis Lions (LJLL)

DOMAIN

Digital Health, Biology and Earth

THEME

Modeling and Control for Life Sciences

Inria

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Project-Team COMMEDIA

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

A6.1.4. – Multiscale modeling

A6.1.5. – Multiphysics modeling

A6.2.1. – Numerical analysis of PDE and ODE

A6.3.1. – Inverse problems

A6.3.2. – Data assimilation

A6.3.4. – Model reduction

Other research topics and application domains

B2.2.1. – Cardiovascular and respiratory diseases

B2.4.1. – Pharmaco kinetics and dynamics

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2 Overall objectives

COMMEDIA is a joint project-team of the Inria Research Center of Paris and the Jacques-Louis Lions Laboratory (LJLL) of Sorbonne Université and CNRS (UMR7598). The research activity of COMMEDIA focuses on the numerical simulation of bio-fluid flows in the human body, more specifically, blood flows in the cardiovascular system and air flows in the respiratory system. These simulations are intended to complement available clinical data with the following purpose: help clinicians or bio-engineers to enhance the understanding of physiological phenomena, to improve diagnosis and therapy planning or to optimize medical devices. The main objectives of COMMEDIA are:

- the development of appropriate mathematical models and efficient numerical methods for the simulations and for the interaction of simulations with measured data;
- the mathematical analysis of these models and numerical techniques;
- the development and validation of scientific computing software which implements these numerical techniques.

A distinctive feature of the mathematical models considered in COMMEDIA is that they often couple different types of partial differential equations (PDEs). This heterogeneous character in the models is a mathematical manifestation of the multi-physics nature of the considered problems.

3 Research program

3.1 Multi-physics modeling and simulation

The research activity in terms of modeling and simulation (i.e., the so-called forward problem) is driven by two application domains related to the cardiovascular and the respiratory systems.

3.1.1 Cardiovascular hemodynamics

We distinguish between *cardiac hemodynamics* (blood flow inside the four chambers of the heart) and *vascular hemodynamics* (blood flow in the vessels of the body).

Cardiac hemodynamics. The numerical simulation of cardiac hemodynamics presents many difficulties. We can mention, for instance, the large deformation of the cardiac chambers and the complex fluid-structure interaction (FSI) phenomena between blood, the valves and the myocardium. Blood flow can be described by the incompressible Navier-Stokes equations which have to be coupled with a bio-physical model of the myocardium electro-mechanics and a mechanical model of the valves. The coupling between the fluid and the solid media is enforced by kinematic and dynamic coupling conditions, which guarantee the continuity of velocity and stresses across the interface. In spite of the significant advances achieved since the beginning of this century (see, e.g., [62, 63, 60, 65, 53]), the simulation of all the fluid-structure interaction phenomena involved in the heart hemodynamics remains a complex and challenging problem.

Heart valves are definitely a bottleneck of the problem, particularly due to their fast dynamics and the contact phenomena with high pressure-drops. Computational cost is recognized as one of the

key difficulties, related to the efficiency of the FSI coupling method and the robustness of the contact algorithm. Furthermore, the numerical discretization of these coupled systems requires to deal with unfitted fluid and solid meshes, which are known to complicate the accuracy and/or the robustness of the numerical approximations (see Section 3.3.2 below).

The ultimate goal of the proposed research activity is the simulation of the complete fluid-structure-contact interaction phenomena involved within the heart. Most of this work will be carried out in close collaboration with the M3DISIM project-team, which has a wide expertise on the modeling, simulation and estimation of myocardium electro-mechanics. We will also consider simplified approaches for cardiac hemodynamics (see, e.g., [35, 48, 51]). The objective is to develop mathematically sound models of reduced valve dynamics with the purpose of enhancing the description of the pressure dynamics right after the opening/closing of the valve (traditional models yield spurious pressure oscillations).

Vascular hemodynamics. The modeling and simulation of vascular hemodynamics in large vessels has been one of the core research topics of some members of COMMEDIA, notably as regards the fluid-structure interaction phenomena. Here we propose to investigate the modeling of pathological scenarios, such as the hemorrhage phenomena in smaller vessels. Modeling of hemorrhage is motivated by the medical constatation that, after a primary vessel wall rupture, secondary vessel wall ruptures are observed. Biologists postulate that the mechanical explanation of this phenomenon might be in the change of applied stress due to blood bleeding. We propose to model and simulate the underlying coupled system, blood vessel flow through the external tissue, to estimate the effect of the subsequent stress variation.

3.1.2 Respiratory flows

The motivation of the proposed research activities is to develop a hierarchy of easily parametrizable models allowing to describe and efficiently simulate the physical, mechanical and biological phenomena related to human respiration, namely, ventilation, particle deposition, gas diffusion and coupling with the circulatory system.

Ventilation. The current modeling approaches (either 3D–0D coupled models where the 3D Navier-Stokes equations are solved in truncated geometries of the bronchial tree with appropriate lumped boundary conditions, or 0D–3D coupled models where the lung parenchyma is described by a 3D elastic media irrigated by a simplified bronchial tree) provide satisfactory results in the case of mechanical ventilation or normal breathing. Realistic volume-flow phase portraits can also be simulated in the case of forced expiration (see [37, 45, 68]), but the magnitude of the corresponding pressure is not physiological. The current models must be enriched since they do not yet correctly describe all the physiological phenomena at play. We hence propose to extend the 0D–3D (bronchial tree–parenchyma) model developed in the team, by considering a non-linear, viscoelastic and possibly poro-elastic description of the parenchyma with appropriate boundary conditions that describe ribs and adjacent organs and taking into account an appropriate resistive model.

So far, the motion of the trachea and proximal bronchi has been neglected in the ventilation models (see, e.g., [70]). These features can be critical for the modeling of pathologic phenomena such as sleep apnea and occlusion of the airways. This would be a long-term goal where fluid-structure interaction and the possible contact phenomena will be taken into account, as in the simulation of cardiac hemodynamics (see Section 3.1.1).

Aerosol and gas diffusion. The dynamics of aerosols in the lung have been widely studied from the mathematical modeling standpoint. They can be described by models at different scales: the microscopic one for which each particle is described individually, the mesoscopic (or kinetic) one for which a density of probability is considered, or the macroscopic one where reaction-diffusion equations describing the behavior of the constituant concentration are considered. The objective of COMMEDIA will mainly be to develop the kinetic approach that allows a precise description of the deposition area at controlled computational costs. Part of this study could be done in collaboration with colleagues from the Research Center for Respiratory Diseases at Inserm Tours (UMR1100).

The macroscopic description is also appropriate for the diffusion of gases (oxygen and carbon dioxide) in the bronchial tree (see [64]). Regarding the influence of the carrier gas, if the patient inhales a different mixture of air such as a Helium-Oxygen mixture, the diffusion mechanisms could be modified. In this context, the goal is to evaluate if the cross-diffusion (and thus the carrier gas) modifies the quantities of oxygen diffused. Part of this work will be carried out in collaboration with members of the LJLL and of the

MAP5.

As a long term goal, we propose to investigate the coupling of these models to models of diffusion in the blood or to perfusion models of the parenchyma, and thus, have access thanks to numerical simulations to new indices of ventilation efficiency (such as dissolved oxygen levels), depending on the pathology considered or the resting or exercise condition of the patient.

3.2 Simulation with data interaction

The second research axis of COMMEDIA is devoted to the interaction of numerical simulations with measured data. Several research directions related to two specific applications are described below: blood flows and cardiac electrophysiology, for which the mathematical models have been validated against experimental data. This list is not exhaustive and additional problems (related to cardiac and respiratory flows) shall be considered depending on the degree of maturity of the developed models.

3.2.1 Fluid flow reconstruction from medical imaging

A first problem which is currently under study at COMMEDIA is the reconstruction of the flow state from Doppler ultrasound measurements. This is a cheap and largely available imaging modality where the measure can be interpreted as the average on a voxel of the velocity along the direction of the ultrasound beam. The goal is to perform a full-state estimation in a time compatible with a realistic application.

A second problem which is relevant is the flow and wall dynamics reconstruction using 4D-flow MRI. This imaging modality is richer than Doppler ultrasound and provides directly a measure of the 3D velocity field in the voxels. This enables the use of direct estimation methods at a reduced computational cost with respect to the traditional variational data assimilation approaches. Yet, the sensitivity of the results to subsampling and noise is still not well understood.

We also propose to address the issues related to uncertainty quantification. Indeed, measurements are corrupted by noise and the parameters as well as the available data of the system are either hidden or not known exactly (see [59]). This uncertainty makes the estimation difficult and has a large impact on the precision of the reconstruction, to be quantified in order to provide a reliable tool.

3.2.2 Safety pharmacology

One of the the most important problems in pharmacology is cardio-toxicity (see [58]). The objective is to predict whether or not a molecule alters in a significant way the normal functioning of the cardiac cells. This problem can be formulated as inferring the impact of a drug on the ionic currents of each cell based on the measured electrical signal (e.g., electrograms from Micro-Electrodes Arrays). The proposed approach in collaboration with two industrial partners (NOTOCORD and Ncardia) consists in combining available realistic data with virtual ones obtained by numerical simulations. These two datasets can be used to construct efficient classifiers and regressors using machine learning tools (see [42]) and hence providing a rapid way to estimate the impact of a molecule on the electrical activity. The methodological aspects of this work are addressed in Section 3.3.3.

3.3 Methodological core

The work described in this section is aimed at investigating fundamental mathematical and numerical problems which arise in the first two research axes.

3.3.1 Mathematical analysis of PDEs

The mathematical analysis of the multi-scale and multi-physics models are a fundamental tool of the simulation chain. Indeed, well-posedness results provide precious insights on the properties of solutions of the systems which can, for instance, guide the design of the numerical methods or help to discriminate between different modeling options.

Fluid-structure interaction. Most of the existing results concern the existence of solutions locally in time or away from contacts. One fundamental problem, related to the modeling and simulation of valve dynamics (see Sections 3.1.1 and 3.3.2), is the question of whether or not the model allows for contact

(see [57, 55]). The proposed research activity is aimed at investigating the case of both immersed rigid or elastic structures and explore if the considered model allows for contact and if existence can be proved beyond contact. The question of the choice of the model is crucial and considering different types of fluid (Newtonian or non-Newtonian), structure (smooth or rough, elastic, viscoelastic, poro-elastic), or various interface conditions has an influence on whether the model allows contact or not.

Fluid–structure mixture. The main motivation to study fluid-solid mixtures (i.e., porous media consisting of a skeleton and connecting pores filled with fluid) comes from the modeling of the lung parenchyma and cerebral hemorrhages (see Sections 3.1.1–3.1.2). The Biot model is the most widely used in the literature for the modeling of poro-elastic effects in the arterial wall. Here, we propose to investigate the recent model proposed by the M3DISIM project-team in [47], which allows for nonlinear constitutive behaviors and viscous effects, both in the fluid and the solid. Among the questions which will be addressed, some of them in collaboration with M3DISIM, we mention the justification of the model (or its linearized version) by means of homogenization techniques and its well-posedness.

Fluid–particle interaction. Mathematical analysis studies on the Navier-Stokes-Vlasov system for fluid-particle interaction in aerosols can be found in [39, 41]. We propose to extend these studies to more realistic models which take into account, for instance, changes in the volume of the particles due to humidity.

3.3.2 Numerical methods for multi-physics problems

In this section we describe the main research directions that we propose to explore as regards the numerical approximation of multi-physics problems.

Fluid-structure interaction. The spatial discretization of fluid-structure interaction (FSI) problems generally depends on the amount of solid displacement within the fluid. Problems featuring moderate interface displacements can be successfully simulated using (moving) fitted meshes with an arbitrary Lagrangian-Eulerian (ALE) description of the fluid. This facilitates, in particular, the accurate discretization of the interface conditions. Nevertheless, for problems involving large structural deflections, with solids that might come into contact or that might break up, the ALE formalism becomes cumbersome. A preferred approach in this case is to combine a Eulerian formalism in the fluid with an unfitted mesh discretization, in which the fluid-structure interface deforms independently of a background fluid mesh. In general, traditional unfitted mesh approaches (such as the immersed boundary and the fictitious domain methods [67, 38, 54, 36]) are known to be inaccurate in space. These difficulties have been recently circumvented by a Nitsche-based cut-FEM methodology (see [33, 43]). The superior accuracy properties of cut-FEM approaches comes at a price: these methods demand a much more involved computer implementation and require a specific evaluation of the interface intersections.

As regards the time discretization, significant advances have been achieved over the last decade in the development and the analysis of time-splitting schemes that avoid strong coupling (fully implicit treatment of the interface coupling), without compromising stability and accuracy. In the vast majority of these studies, the spatial discretization is based on body fitted fluid meshes and the problem of accuracy remains practically open for the coupling with thick-walled structures (see, e.g., [52]). Within the unfitted mesh framework, splitting schemes which avoid strong coupling are much more rare in the literature.

Computational efficiency is a major bottleneck in the numerical simulation of fluid-structure interaction problems with unfitted meshes. The proposed research activity is aimed at addressing these issues. Another fundamental problem that we propose to face is the case of topology changes in the fluid, due to contact or fracture of immersed solids. This challenging problem (fluid-structure-contact-fracture interaction) has major role in many applications (e.g., heart valves repair or replacement, break-up of drug-loaded micro-capsules) but most of the available studies are still merely illustrative. Indeed, besides the numerical issues discussed above, the stability and the accuracy properties of the numerical approximations in such a singular setting are not known.

Fluid–particle interaction and gas diffusion. Aerosols can be described through mesoscopic equations of kinetic type, which provide a trade-off between model complexity and accuracy. The strongly coupled fluid-particle system involves the incompressible Navier-Stokes equations and the Vlasov equation. The proposed research activity is aimed at investigating the theoretical stability of time-splitting schemes for this system. We also propose to extend these studies to more complex models that take into account the radius growth of the particles due to humidity, and for which stable, accurate and mass

conservative schemes have to be developed.

As regards gas diffusion, the mathematical models are generally highly non-linear (see, e.g., [64, 66, 40]). Numerical difficulties arise from these strong non linearities and we propose to develop numerical schemes able to deal with the stiff geometrical terms and that guarantee mass conservation. Moreover, numerical diffusion must be limited in order to correctly capture the time scales and the cross-diffusion effects.

3.3.3 Statistical learning and mathematical modeling interactions

Machine learning and in general statistical learning methods (currently intensively developed and used, see [34]) build a relationship between the system observations and the predictions of the QoI (quantities of interest) based on the *a posteriori* knowledge of a large amount of data. When dealing with biomedical applications, the available observations are signals (think for instance to images or electro-cardiograms, pressure and Doppler measurements). These data are high dimensional and the number of available individuals to set up precise classification/regression tools could be prohibitively large. To overcome this major problem and still try to exploit the advantages of statistical learning approaches, we try to add, to the a posteriori knowledge of the available data an *a priori* knowledge, based on the mathematical modeling of the system. A large number of numerical simulations is performed in order to explore a set of meaningful scenarios, potentially missing in the dataset. This *in silico* database of virtual experiments is added to the real dataset: the number of individuals is increased and, moreover, this larger dataset can be used to compute semi-empirical functions to reduce the dimension of the observed signals.

Several investigations have to be carried out to systematically set up this framework. First, often there is not a single mathematical model describing a physiological phenomenon, but hierarchies of models of different complexity. Every model is characterized by a model error. How can this be accounted for? Moreover, several statistical estimators can be set up and eventually combined together in order to improve the estimations (see [61]). Other issues have an actual impact and has to be investigated: what is the optimal number of *in silico* experiments to be added? What are the most relevant scenarios to be simulated in relation to the statistical learning approach considered in order to obtain reliable results? In order to answer to these questions, discussions and collaborations with statistics and machine learning groups have to be developed.

3.3.4 Tensor approximation and HPC

Tensor methods have a recent significant development because of their pertinence in providing a compact representation of large, high-dimensional data. Their applications range from applied mathematics and numerical analysis to machine learning and computational physics. Several tensor decompositions and methods are currently available (see [56]). Contrary to matrices, for tensors of order higher or equal to three, there does not exist, in general, a best low rank approximation, the problem being ill posed (see [69]). Two main points will be addressed: (i) The tensor construction and the multi-linear algebra operations involved when solving high-dimensional problems are still sequential in most of the cases. The objective is to design efficient parallel methods for tensor construction and computations; (ii) When solving high-dimensional problems, the tensor is not assigned; instead, it is specified through a set of equations and tensor data. Our goal is to devise numerical methods able to (dynamically) adapt the rank and the discretization (possibly even the tensor format) to respect the chosen error criterion. This could, in turn, improve the efficiency and reduce the computational burden.

These sought improvements could make the definition of parsimonious discretizations for kinetic theory and uncertainty quantification problems (see Section 3.2.1) more efficient and suitable for a HPC paradigm. This work will be carried out in collaboration with Olga Mula (TU Eindhoven) and MATHERIALS project-teams.

4 Application domains

4.1 Cardiovascular hemodynamics

The heart is a double pump whose purpose is to deliver blood to the tissue and organs of the body. This function is made possible through the opening and closing of the heart valves. Cardiac diseases generally manifest by affecting the pumping function of the heart. Numerical simulations of cardiac hemodynamics, in normal and pathological conditions, are recognized as a tool of paramount importance for improving the understanding, diagnosis and treatment of cardiac pathologies, and also for the development of implantable devices (see, e.g., [65, 46]). As an example, we can mention the case of cardiac mitral valve regurgitation, one of the most common heart valve diseases. For this pathology, clinical data are known to be insufficient for determining the optimal timing for surgery, the best surgical strategy and the long-term outcome of a surgical repair. Contrary to imaging techniques, numerical simulations provide local information, such as pressure and stresses, which are of fundamental importance for the prediction of the mechanical behavior of native valves and of implantable devices.

4.2 Respiratory flows

Respiration involves the transport of air through the airways from the mouth to the alveoli of the lungs. These units where diffusion of oxygen and carbon dioxide takes place, are surrounded by a viscoelastic medium (the parenchyma) consisting of blood vessels and collagen fibers. Air flows due to the displacement of the diaphragm, which drives the pulmonary parenchyma. Accidental inhalations of foreign bodies or pathologies such as asthma, emphysema and fibrosis might prevent the lung of fulfilling its function. Therapies mostly use aerosols (set of small particles, solid or liquid), which must reach the specific areas of the lung targeted for treatment. Understanding the airflow mechanisms within the respiratory network is a fundamental ingredient for predicting the particles motion and their deposition (see, e.g., [44]). Moreover, understanding of the gas diffusion in the lung is also of major importance since the main function of this organ is to deliver oxygen to the blood.

4.3 Safety pharmacology

The problem of safety pharmacology can be summarized as follows: given a molecule which is a candidate to become a drug, is its use dangerous due to side effects? Among all the different problems to be addressed, one of the most relevant questions in pharmacology is cardio-toxicity (see [58]). More precisely, the objective is to determine whether or not a molecule alters in a significant way the normal functioning of the cardiac cells. To answer these questions, the CiPA initiative promotes the introduction of novel techniques and their standardisation (see [50]). One of the proposed tests of the CiPA panel is to measure the electrical activity using Micro-Electrodes Array: these are microchips that record the electrical activity of an ensemble of cells. The task is to infer the impact of a drug on the ionic currents of each cell based on the electrical signal measured (electrograms) and, in perspective, to be able to assess whether a molecule can induce arrhythmia (see [49]).

5 New software, platforms, open data

5.1 New software

5.1.1 FELiScE

Name: Finite Elements for Life SCiences and Engineering problems

Keywords: Finite element modelling, Cardiac Electrophysiology, Cardiovascular and respiratory systems

Functional Description: FELiScE is a finite element developed by COMMEDIA project-team. 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 open source, and may be later released as an opensource library. FELiScE 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.

URL: https://team.inria.fr/commedia/software/felisce/

Contact: Miguel Angel Fernandez Varela

Participants: Romain Lemore, Marguerite Champion, Daniele Carlo Corti, Miguel Angel Fernandez Varela, Marina Vidrascu, Sara Costa Faya, Oscar Ruz, Fabien Lespagnol, Carlos Brito Pacheco

5.1.2 FELiScE-NS

Keywords: Thin-walled solids, Incompressible flows

Functional Description: FELiScE-NS is a set of finite elements solvers for incompressible fluids (fractional-step schemes) and non-linear thin-walled structures (3D shells, and 2D curved beams) developed in the framework of the FELiScE library. FELiSCe-NS was registered in 2018 at the Agence pour la Protection des Programmes Inter Deposit Digital Number IDDN.FR.001.270015.000.S.A.2018.000.31200.

Contact: Miguel Angel Fernandez Varela

Participants: Oscar Ruz, Fabien Lespagnol, Miguel Angel Fernandez Varela, Marina Vidrascu, Daniele Carlo Corti, Sara Costa Faya

5.1.3 ADAPT

Name: Adaptive Dynamical Approximation via Parallel Tensor methods

Keywords: Scientific computing, Tensor decomposition, Partial differential equation

Functional Description: ADAPT is a library containing methods for scientific computing based on tensors. In many fields of science and engineering we need to approximate the solution of high-dimensional problems. In this library we propose a collection of methods to parsimoniously discretise high-dimensional problems. These methods are mainly based on tensors.

Contact: Damiano Lombardi

Participants: Virginie Ehrlacher, Damiano Lombardi, Sebastien Riffaud

6 New results

6.1 Reduced Order modelling

Participants: Damiano Lombardi.

In [29] we investigated the parsimonious representation of sets of functions defined on varying domains, with a particular focus on the characteristic functions of the domains itselves. The set of characteristic functions is known to have slowly decaying Kolmogorov witdths, making it unpractical to use linear approximation methods to represent them. In this work we propose a method in which we correct the linear approximation by building ridge functions. The whole method can be cast in a form of an encoder-decoder pair, in which the encoder is linear, and the decoder is non-linear. Contrary to what is usually done, the non-linearity is not fixed a priori. Instead, we look for the non-linearity in the class of piece-wise polynomial functions, and, in particular, component-wise $\mathbb{P}^3$–Hermite. This makes it possible to prove that the correction will actually improve, by construction, the linear reconstruction. We proposed a greedy method in order to build the non-linear correction on the basis of error and parsimony criteria,

leading to a certified method for the representation of the database elements. The theoretical results made it possible to understand that the method is efficient in cases in which the characteristic functions of the domains vary around a reference configuration in a relatively sparse way. The numerical tests in 1d, 2d, 3d confirmed this. This situation is typically the one encountered when considering segmented geometries. In this respect, the method can be considered as a first step to define low-dimensional intrinsic parametrisations of sets of segmented geometries, in a systematic way.

6.2 Safety pharmacology

Participants: Sara Costa Faya, Miguel Angel Fernandez Varela, Damiano Lombardi, Marina Vidrascu.

In [27] we investigated a mathematical model of arterial tissue and its ability to describe ex-vivo experiments which are used in pharmacology to assess the impact of vaso-contrictors and vaso-dilators on the arterial walls. The mathematical model is based on a 3D-shell formulation, with an Ogden constitutive law, to which we added two layers of active fibers to model the smooth muscle cells. The parameters of the model are calibrated by using experimental data. We made several contributions. First, we used different experimental modalities to find the parameters values of both passive and active parts of the structure. This made it possible to test some hypotheses on the action of the molecules on the arterial wall. In particular, we could conclude that vaso-constrictors and vaso-dilators mainly affect the smooth muscle cells, and only partially, and indirectly, the endothelium. Second, we validated the results on unseen data. The prediction error made it possible to assess the validity of the model and to suggest possible ways to improve it, to better represent the physiological behaviour of the tissue.

6.3 Mathematical analysis of PDEs

Participants: Céline Grandmont.

In [28] we study an unsteady non-linear fluid-structure interaction problem where a two-dimensional viscous incompressible Newtonian fluid and a mono-dimensionnal elastic structure, located on one part of the fluid domain boundary interact. The fluid motion is modelled by the two-dimensional incompressible Navier-Stokes equations set in an unknown domain which depends on the structure's displacement. We consider longitudinal as well as transversal structure displacements. We assume that the longitudinal displacement of the structure satisfies a wave equation whereas the transversal displacement follows a beam equation with inertia of rotation. The fluid and structure systems are coupled through a kinematic condition which corresponds to a no-slip condition at the fluid-structure interface and the fluid exerts a force on the elastic structure. We prove the existence and uniqueness of strong solution to the considered problem with no gap between the initial conditions regularity and the ones obtained in positive time. To our knowledge, this is the first result regarding existence and uniqueness of strong solutions for fluid-beam interaction problem in the unsteady case taking into account both the transversal displacement and the longitudinal structure displacement.

6.4 Numerical methods for multi-physics problems

Participants: Daniele Corti, Miguel Angel Fernández Varela, Céline Grandmont, Oscar Ruz , Marina Vidrascu.

In [23] we propose and analyse a new scheme to discretize the linearized version of a rather general poromechanics model adapted to biological tissues perfusion. This model, which is related to – albeit different from – Biot equations, involves unsteady solid and fluid momentum balance equations that are

further coupled through an incompressibility constraint, a pore pressure and permeability terms. The key feature of the scheme is to decouple the solid, fluid and pressure unknowns at each time step by means of a projection method, composed of a prediction and a correction step. We perform a complete stability analysis of the scheme depending on the implicit or explicit treatment of friction and pressure in the prediction step. Several boundary conditions are considered, including conditions coupling the solid and fluid phases on the boundary that are imposed at the discrete level using a Robin-Robin method. In the case of Dirichlet boundary conditions, we also provide a fully discrete error estimate as long as a discrete inf-sup condition is satisfied. The scheme properties and robustness with respect to physical parameters are illustrated by numerical experiments. Finally, its computational performance is compared with that of a monolithic approach.

The combination of reduced models of cardiac valve dynamics with a one-way kinematic uncoupling of blood flow and electromechanics is a widespread approach for reducing the complexity of cardiac hemodynamics simulations. This comes however with a number of shortcomings: artificial pressure oscillations, missing isovolumetric phases and valve laws without precise continuous formulation. In [32] we overcome these three difficulties while still mitigating computational cost. A novel reduced model of valve dynamics is proposed in which unidirectional flow is enforced in a mathematically sound fashion. Artificial pressure oscillations are overcome by considering a fluid-structure interaction model, which couples bi-ventricular electromechanics and blood flow in the left cavities. The interface coupling is solved in a partitioned fashion via an unconditionally stable loosely coupled scheme. A priori energy estimates are derived for both the continuous coupled problem and its numerical approximation. The benefits and limitations of the proposed approaches are illustrated in a comprehensive numerical study.

In [26], we extend the low-order fictitious domain method with enhanced mass conservation presented in [ESAIM: Math. Model. Numer. Anal., 58(1):303-333, 2024] to the case of coupling with immersed thin-walled solids. Both surface and 3D-shell models are considered for the description of the solid, including contact between solids. For both models, the interface coupling is enforced on the mid-surface of the shell using a stabilized Lagrange multiplier formulation. Numerical examples in both two and three dimensions illustrate the effectiveness of the method, including its successful application to the simulation of aortic heart valve dynamics.

In [12], we consider a loosely coupled, non-iterative Robin-Robin coupling method proposed and analyzed in [J. Numer. Math., 31(1):59–77, 2023] for a parabolic-parabolic interface problem and prove estimates for the discrete time derivatives of the scalar field in different norms. When the interface is flat and perpendicular to two of the edges of the domain we prove error estimates in the H2-norm. Such estimates are key ingredients to analyze a defect correction method for the parabolic-parabolic interface problem. Numerical results are shown to support our findings.

In [11], we consider a parabolic-parabolic interface problem and construct a loosely coupled prediction-correction scheme based on the Robin-Robin splitting method analyzed in [J. Numer. Math., 31(1):59–77, 2023]. We show that the errors of the correction step converge at second-order, under suitable convergence rate assumptions on the discrete time derivative of the prediction step. Numerical results are shown to support our analysis and the assumptions.

6.5 Inverse problems

Participants: Guillaume Delay, Corrie James, Damiano Lombardi
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In [24] we investigated numerical methods to approximate the solution of the unique continuation for the Stokes problem in a situation in which, on top of the knowledge of the mathematical model, we have access to a database of measurements. We consider a critical situation, in which the database does not contain pairs observation-reconstruction, but only noisy observations of the flow velocity in a subdomain. The method proposed consists in using the database in order to build a regularisation for the inverse problem. In this work we made several contributions. First, a stability analysis is proposed, in which we showed that, dispite the fact that the database is not rich, it may contribute to alleviate the ill-posedness of the problem. Second, the analysis showed that the regularisation term can substitute other forms of primal stabilisation of the inverse problem. Third, we considered a model of observations

in which we do not have infinite spacial resolution (which is closer to realistic situations), and we studied from a numerical point of view how this is in interplay with the regularisation of the inverse problem, and how it affects the results. Lastly, the regularisation proposed consists in identifying a possibly low-dimensional subspace to which the solutions are closed to. To generate it, as the database solely contains observations in a subdomain, we have to solve an extension problem. The nature of the fields points towards the use of an optimal recovery formulation, which was solved through a Riesz-Galerkin method and a Chambolle-Pock proximal iteration. The numerical tests, 2d and 3d, showed that the proposed regularisation is effective in reducing the reconstruction error with respect to the classical method, whenever the information of the database can be exploited.

In [25] we propose and analyse a numerical method to solve the unique continuation problem subject to the wave equation. Our main result proves the convergence of the discrete solution to the exact solution in a shifted energy norm involving weaker Sobolev norms than the standard energy norm for the wave equation.

6.6 Tensor approximation and HPC

Participants: Damiano Lombardi.

In [31] we consider the discretisation of linear parametric Partial Differential Equations (PDEs). A very large class of PDEs and classical discretisations leads to parametric linear systems which can be cast as a linear system written as a sum Kronecker products of sparse matrices. When the parametric solutions are expressed in a low-rank format, the problem takes the form of a multi-linear problem. The matrix-vector multiplication can be performed in an efficient way, and this suggests the use of Krylov-based mathods to obtain an approximation of the parametric solution. For these methods, the preconditioning step is of paramount importance. In this work we analysed and tested three different preconditioning strategies. The first one and the second one are based on the Voronoi quantisation of the parametric space, and are similar, to some extent, to methods proposed in the literature. The third one, which is novel to the authors knowledge, is based on the definition of a fixed-point iteration. We analysed these preconditioning strategies and the theoretical results shed some light on the preconditioning mechanisms. The numerical tests confirmed that the preconditioners play a fundamental role, making it possible to reduce the norm of the non-preconditioned residual of several orders of magnitude, for the same computational cost.

6.7 Miscellaneous

Participants: Miguel Angel Fernández Varela, Damiano Lombardi.

In [30] we investigated a mixed variational formulation to perform a semi-discretisation in space of Partial Differential Equations (PDEs) which are composed of two parts: one, Hamiltonian, carrying conservations, and the other, a gradient flow, taking into account dissipation mechanisms. The goal is to study the possibility of setting up, systematically, a conformal variational structure-preserving discretisation: we analysed how and under which conditions the mixed formulation leads to a finite dimensional dynamical system composed of a finite dimensional Hamiltonian part and a finite dimensional gradient flow. Moreover, we proposed theoretical results on the equivalence between the mixed formulation and the classical variational formulation of the problem, the conservation of Casimirs of the Hamiltonian part, of invariants and equilibria of the system. We studied the convergence of the method and some properties of two time discretisations. We tested the analysed formulation on two PDEs: the Korteweg-de-Vries equation, and the incompressible Navier-Stokes equations in vorticity formulation (both on the 2d-torus and the sphere). The numerical tests made it possible to assess the properties of the analysed formulation. This has to be considered a first step towards the definition of structure-preserving variational discretisations for high-dimensional and parametric PDEs.

In [22] we propose an error analysis for a numerical approximation of the the transient Stokes problem which combines an incremental pressure-correction fractional-step scheme in time with a PSPG (pressure

stabilized Petrov–Galerkin) finite element method in space. Optimal velocity convergence is obtained for affine approximations, whereas an inverse CFL condition is required with high-order polynomials and for the pressure.

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

Withings

Participants: Miguel Ángel Fernández Varela *(coordinator)*, Adrien Lefieux, Damiano Lombardi, Marina Vidrascu, Fabien Vergent.

This research project has the objective of developing mathematical models of photoplethysmography (PPG) measurements in the wrist and their connection to blood pressure estimation.

CASIS

Participants: Miguel Ángel Fernández Varela *(coordinator)*, Damiano Lombardi, Romain Lemore.

Calibration of vascular fluid-structure interaction simulations from 4D-flow MRI data.

8 Partnerships and cooperations

8.1 International initiatives

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

IMFIBIO

Participants: Daniele Carlo Corti, Guillaume Delay, Miguel Angel Fernández Varela, Oscar Ruz.

Title: Innovative Methods for Forward and Inverse problems in BIO-medical applications

Duration: 2022–2024

Coordinator: Miguel Angel Fernández Varela

Partners: University College London London (Royaume-Uni)

UCL contact: Erik Burman

Summary: The purpose of the IMFIBIO Associate Team is to exploit the complementary expertise of both partners in mathematical analysis, numerical analysis, scientific computing and data assimilation in order to develop innovative methods for the study of forward and inverse problems in the context of bio-medical applications.

Web site: team.inria.fr/imfibio

8.1.2 Visits of international scientists

- Erik Burman (UCL), April, October, Decmber 2024.
- Rodolfo Araya (Universidad de Concepción), April-June 2024.
- Hessam Sam Babaee (University of Pittsburgh), September-October 2024.

8.2 European initiatives

8.2.1 Horizon Europe

INSPIRE

Participants: Sara Costa, Miguel Angel Fernández Varela, Haibo Liu, Marina Vidrascu, Damiano Lombardi.

Title: INnovation in Safety Pharmacology for Integrated cardiovascular safety assessment to REduce adverse events and late stage drug attrition

Duration: 2020–2024

Coordinator: University of Antwerp

Local coordinator: Damiano Lombardi

Summary: INSPIRE is an European Training Network (ETN) projet funding 15 Early Stage Researchers (ESRs) aimed to exploit innovative techniques for better assessment and prediction of cardiovascular safety liabilities.

Web site: www.uantwerpen.be/en/projectsinspire-safety-pharmacology

8.3 National initiatives

SIMR: Simulation and Imaging for Mitral Regurgitation

Participants: Daniele Carlo Corti, Miguel Angel Fernández Varela, Marina Vidrascu, Céline Grandmont.

Funding: ANR PRC

Duration: 2020-2024

Coordinator: Miguel Angel Fernández Varela

Partners: CREATIS, HCL, LGEF, M3DISIM, TIMC

Summary: The SIMR project aims at evaluating the physical consequences of mitral repair using efficient numerical simulations, advanced imaging techniques and an innovative measurement tools in a clinical study

CoCop: Heart-Lung Coupling: aid to monitor cardio-respiratory functions in intensive care

Participants: Céline Grandmont, Frédérique Noël, Fabien Vergnet, Romain Lopez-Surjus.

Funding: Inria Exploratory Actions

Duration: 2024–2027

Coordinator: Céline Grandmont

Partners: MEDISIM project-team (D. Chapelle, P. Moireau), APHP Lariboisière Hospital (F. Vallée)

Summary: The project seeks to respond to the clinical need for a better understanding of cardio-respiratory functions for patients placed under mechanical ventilation. It aims in particular to propose ventilatory maneuvers or minimally invasive measurements that can be carried out at the bedside of patients, making it possible to estimate the condition of the lung, the level of blood perfusion and help optimize ventilator settings in order to minimize damage to the lungs.

MediTwin

Participants: Carlos Brito Pacheco, Miguel Angel Fernandez Varela, Damiano Lombardi, Marina Vidrascu.

Funding: BPI

Duration: 2024-2029

Local coordinator: Miguel Angel Fernández Varela

Partners: Dassault Systems, SIMBIOTX projec-team, M3DISIM project-team

Summary: 3D modeling and simulation of cardiac hemodynamics, notably of patohological scenarios such as the Hypoplastic Left Heart Syndrome (HLHS), whith the purpose of assesing different surgicals options.

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

- Guillaume Delay
  - Co-organizer of the scientific computing seminar, joint event between Inria and Laboratoire Jacques-Louis Lions.
  - Mini-symposium co-organizer, *Immersed boundary methods*, in CANUM 2024, Ile de Ré, May 2024.
- Miguel Angel Fernández Varela
  - Co-organizer of Mini-symposium *New trends in the Mathematical and Numerical aspects of Fluid-Structure Interaction*, ECCOMAS Congress 2024, Lisbon, June 2024.
- Céline Grandmont
  - Member of organizing comitte of a Workshop on fluid-structure interaction, Janvier 2024, ULB
- Damiano Lombardi
  - Co-organizer of the scientific computing seminar, joint event between Inria and Laboratoire Jacques-Louis Lions.
  - Mini-symposium co-organizer (with F. Nobile, EPFL) *Low Rank Methods for Random Dynamical Systems and Sequential Data Assimilation.*, SIAM UQ 2024, Trieste, 02-2024.
  - Co-president of CES (Commission Emploi Scientifique), INRIA.
  - Scientific committee of *Journées Lions-Magenes 2024*, Pavia, 05-2024.
- Fabien Vergnet
  - Mini-symposium co-organizer, *Immersed boundary methods*, in CANUM 2024, Ile de Ré, May 2024.
- Marina Vidrascu
  - Co-organizer of Mini-symposium *New trends in the Mathematical and Numerical aspects of Fluid-Structure Interaction*, ECCOMAS Congress 2024, Lisbon, June 2024.

Member of the conference program committees

- Céline Grandmont
  - Member of the CS of Journées Math Bio Santé 2024.

9.1.2 Journal

Member of the editorial boards

- Céline Grandmont
  - Mathematical Modelling of Natural Phenomena
  - Journal of Mathematical Fluid Mechanics
  - M2AN

9.1.3 Invited talks

- Marguerite Champion
  - Invited speaker, Lions-Magenes days, Pavia, May 2024.
  - Contributed talk in minisymposium, ECCOMAS Congress 2024, Lisbon, June 2024.
- Guillaume Delay
  - Seminar laboratoire Paul Painlevé, Lille, December 2024
  - Invited talk in *POEMS: POlytopal Element Methods in Mathematics and Engineering*, Paris December 3-6 2024
  - Invited talk in workshop *Computational methods for Inverse and Ill-posed problems* November 7-8, 2024, London
  - Invited speaker, *Workshop on Frontiers in Finite Element Methods and Applications*, June 10-14, 2024, Suzhou, China
- Miguel Angel Fernández Varela
  - Invited speaker, *Mathematical Models and Numerical Methods for Multiphysics Systems Conference*, May 1-3, 2024, University of Pittsburgh, USA
  - Invited speaker, *Workshop on Frontiers in Finite Element Methods and Applications*, June 10-14, 2024, Suzhou, China
- Sara Costa Faya
  - Talk in workshop *16th World Congress on Computational Mechanics and 4th Pan American Congress on Computational Mechanics*, July 21-26, 2024, Vancouver, Canada
- Céline Grandmont
  - Plenary speaker Canum 2024
- Damiano Lombardi
  - Talk in mini-symposium: SIAM UQ 2024, Trieste, 02-2024.
  - Talk in workshop: *Conformal variational discretisation for infinite dimensional Hamiltonian systems with gradient flow dissipation.*, SNS, Pisa, 04-2024.
  - Talk in workshop: *Uncertainty Quantification for High-Dimensional problems*, CWI Amsterdam, 12-2024.

- Frédérique Noël
  - Invited talk Third Summer School on Economic principles in cell biology, Paris, July 2024.
  - Talk European Conference on Mathematical and Theoretical Biology, Toledo, July 2024
- Marina Vidrascu
  - Invited talk in minisymposium in the 16th French Romanian Colloquium, Bucharest 26-30 August 2024

9.1.4 Scientific expertise

- Miguel Angel Fernández Varela
  - Member of the Project-Teams Committee Bureau, Inria Paris
- Céline Grandmont
  - Member of the Scientific Committee of the thematic network "Math Bio Santé" and of de axis "Mathématiques, Santé, Sciences du Vivant

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

- Licence:
  - Marguerite Champion
    - Numerical analysis, 248h, L3, Sorbonne University
    - Python, 32h, L2, Sorbonne University
  - Guillaume Delay
    - Remise à Niveau en Math à PolyTech Sorbonne L3, (12h)
  - Corrie James
    - Math Tutoring, 9h, L1, Université de Versailles Saint-Quentin-en-Yvelines
  - Gaël le Ruz
    - Linear algebra and ODE, 30h, L3, Polytech Sorbonne, Sorbonne Université.
    - Numerical Analysis for PDE, 12h, L3, Polytech Sorbonne, Sorbonne Université.
  - Fabien Vergnet
    - Numerical analysis and ODE, 56h, L3, Polytech Sorbonne, Sorbonne Université.
    - Fourier Analysis 15h, L3, Polytech Sorbonne, Sorbonne Université.
    - Dynamical Systems 6h, L3, Polytech Sorbonne, Sorbonne Université.
- Master:
  - Guillaume Delay
    - Preparation to Agrégation, 34h, M2, Sorbonne Université
    - Numerical analysis for PDE, 18h, M1,PolyTech Sorbonne
    - Initiation to C++, 27h, M2, Sorbonne Université.
    - C++ projet, 21h, M2, Sorbonne Université.
  - Miguel Angel Fernández Varela
    - Mathematical models and numerical methods for hemodynamics simulations, 20h, M2, Sorbonne Université.

- Damiano Lombardi
  - Lecture, 1.5h, Modeling the electro-physiology of heart, November 2023, Ecole des Mines Paristech.
- Frédérique Noël
  - Programming in C++, 28h, M1, Sorbonne Université

9.2.2 Supervision

- PhD in progress: Oscar Ruz, Mathematical modeling and numerical simulation of left heart hemodynamics with fluid–structure interactions. Supervisors: D. Chapelle, M.A. Fernández Varela & M. Vidrascu.
- PhD in progress: Marguerite Champion, Modeling, analysis and simulation of fluid-structure-contact interaction. Supervisors: M.A. Fernández Varela, C. Grandmont, F. Vergnet & M. Vidrascu.
- PhD in progress: Gaël le Ruz, Observer theory in general constrained spaces – from formulations to applications. Since October 2022. Supervisors: D. Lombardi & P. Moireau.
- PhD in progress: Corrie James, Data-Modeling interaction for biomedical applications. Since October 2023. Supervisors: M. Boulakia & D. Lombardi.
- PhD in progress: Romain Lemore, Modeling and patient specific fluid-structure interaction simulations of aortic pathological configurations. Since July 2024. Supervisors: M.A. Fernández Varela & D. Lombardi.
- PhD in progress: Romain Lopez-Surjus, Mathematical and numerical modelling of the cardio respiratory system. Since October 2024. Supervisors: C. Grandmont, F. Noël & F. Vergnet
- PhD in progress: Davide Duva, A 4D-var method for blood pressure reconstruction. Since December 2024. Supervisors: G. Delay & M.A. Fernández Varela.
- PostDoc in progress: Lamis Sabbagh (ARC-ULB, hosted by ULB), Mathematical analysis of fluid-structure interactions problems. Supervisor: C. Grandmont.
- PhD defended on December 16, 2024: Sara Costa Faya, An in silico approach to monitor and predict haemodynamics during safety pharmacology studies. Supervisors: M.A. Fernández Varela, D.Lombardi.
- PhD defended on June 27, 2024: Daniele Corti, Modeling and numerical simulation of the mitral apparatus. Supervisors: M.A. Fernández Varela, G. Delay , F. Vergnet & M. Vidrascu.
- PhD defended on June 26, 2024: Fabien Lespagnol, A new computational approach for fluid-structure interaction of slender bodies immersed in three-dimensional flow. Supervisors: M. Boulakia, M.A. Fernández Varela, C. Grandmont & Paolo Zunino (MOX, Politecnico de Milano).
- PhD defended on May 2, 2024: Haibo Liu, Data assimilation for high-throughputs creening in safety pharmacology. Supervisors: D. Lombardi & M. Boulakia.
- Internship Riccardo Bianchi. Supervisors: Damiano Lombardi, Stefano Pagani, Politecnico di Milano
- Internship Romain Lopez-Surjus. Supervisors: Frédérique Noël,Fabien Vergnet
- Internship David Duva. Supervisors: G. Delay, M.A. Fernández Varela.
- Internship Leo-Paul Baudet. Supervisors: G. Delay, M.A. Fernández Varela.

9.2.3 Juries

- Céline Grandmont
  - Selection Committee: Professor position Nantes Univ.

9.3 Popularization

9.3.1 Participation in Live events

- Céline Grandmont
  - « 1 scientifique, 1 classe : chiche ! » program, 2h, students from Lycée Jeanne d'Albret (Saint-Germain en Laye), December 3, 2024, Rocquencourt
- Miguel Angel Fernández Varela
  - « 1 scientifique, 1 classe : chiche ! » program, 2h, students from Lycée Jeanne d'Albret (Saint-Germain en Laye), December 3, 2024, Rocquencourt

10 Scientific production

10.1 Major publications

[1] M. Barré, C. Grandmont and P. Moireau. 'Analysis of a linearized poromechanics model for incompressible and nearly incompressible materials'. In: *Evolution Equations and Control Theory* (2022). URL: https://hal.inria.fr/hal-03501526.

[2] L. Boudin, C. Grandmont, B. Grec and S. Martin. 'A coupled model for the dynamics of gas exchanges in the human lung with Haldane and Bohr's effects'. In: *Journal of Theoretical Biology* 573 (2023), p. 111590. DOI: 10.1016/j.jtbi.2023.111590. URL: https://hal.science/hal-03883301.

[3] E. Burman, R. Durst, M. A. Fernández and J. Guzmán. 'Fully discrete loosely coupled Robin-Robin scheme for incompressible fluid-structure interaction: stability and error analysis'. In: *Numerische Mathematik* (5th July 2022). DOI: 10.1007/s00211-022-01295-y. URL: https://hal.science/hal-02893444.

[4] M. Champion, M. A. Fernández, C. Grandmont, F. Vergnet and M. Vidrascu. 'On the analysis of a mechanically consistent model of fluid-structure-contact interaction'. In: *Mathematics in Engineering* 6.3 (2024), pp. 425–467. DOI: 10.3934/mine.2024018. URL: https://hal.science/hal-04229012.

[5] D. Corti, G. Delay, M. A. Fernández, F. Vergnet and M. Vidrascu. 'Low-order fictitious domain method with enhanced mass conservation for an interface Stokes problem'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 58.1 (22nd Feb. 2024), pp. 303–333. DOI: 10.1051/m2an/2023103. URL: https://inria.hal.science/hal-04084162.

[6] V. Ehrlacher, M. Fuente-Ruiz and D. Lombardi. 'SoTT: greedy approximation of a tensor as a sum of Tensor Trains'. In: *SIAM Journal on Scientific Computing* 44.2 (21st Mar. 2022). DOI: 10.1137/20M1381472. URL: https://inria.hal.science/hal-03018646.

[7] F. Lespagnol, C. Grandmont, P. Zunino and M. A. Fernández. 'A mixed-dimensional formulation for the simulation of slender structures immersed in an incompressible flow'. In: *Computer Methods in Applied Mechanics and Engineering* 432 (Aug. 2024), p. 117316. DOI: 10.1016/j.cma.2024.117316. URL: https://inria.hal.science/hal-04318526.

[8] D. Lombardi. 'State estimation in nonlinear parametric time dependent systems using Tensor Train'. In: *International Journal for Numerical Methods in Engineering* (2022). DOI: 10.1002/nme.7067. URL: https://hal.inria.fr/hal-03375811.

[9] S. Riffaud, M. A. Fernández and D. Lombardi. 'A low-rank solver for parameter estimation and uncertainty quantification in linear time dependent systems of Partial Differential Equations'. In: *Journal of Scientific Computing* 99.2 (2024), p. 34. DOI: 10.1007/s10915-024-02488-3. URL: https://inria.hal.science/hal-03908682.

10.2 Publications of the year

International journals

[10] M. Boulakia, C. Grandmont, F. Lespagnol and P. Zunino. 'Mathematical and numerical analysis of reduced order interface conditions and augmented finite elements for mixed dimensional problems'. In: *Computers & Mathematics with Applications* 175 (Dec. 2024), pp. 536–569. DOI: 10.1016/j.camwa.2024.10.028. URL: https://inria.hal.science/hal-03501521.

[11] E. Burman, R. Durst, M. A. Fernández, J. Guzmán and S. Liu. 'A second-order correction method for loosely coupled discretizations applied to parabolic-parabolic interface problems'. In: *IMA Journal of Numerical Analysis* (Sept. 2024). URL: https://hal.science/hal-04530926. In press (cit. on p. 11).

[12] E. Burman, R. Durst, M. A. Fernández, J. Guzmán and S. Liu. 'Estimates of discrete time derivatives for the parabolic-parabolic Robin-Robin coupling method'. In: *Numerical Algorithms* (9th Aug. 2024). DOI: 10.1007/s11075-024-01902-z. URL: https://hal.science/hal-04530917 (cit. on p. 11).

[13] M. Champion, M. A. Fernández, C. Grandmont, F. Vergnet and M. Vidrascu. 'On the analysis of a mechanically consistent model of fluid-structure-contact interaction'. In: *Mathematics in Engineering* 6.3 (2024), pp. 425–467. DOI: 10.3934/mine.2024018. URL: https://hal.science/hal-04229012.

[14] D. Corti, G. Delay, M. A. Fernández, F. Vergnet and M. Vidrascu. 'Low-order fictitious domain method with enhanced mass conservation for an interface Stokes problem'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 58.1 (22nd Feb. 2024), pp. 303–333. DOI: 10.1051/m2an/2023103. URL: https://inria.hal.science/hal-04084162.

[15] F. Lespagnol, C. Grandmont, P. Zunino and M. A. Fernández. 'A mixed-dimensional formulation for the simulation of slender structures immersed in an incompressible flow'. In: *Computer Methods in Applied Mechanics and Engineering* 432 (Aug. 2024), p. 117316. DOI: 10.1016/j.cma.2024.117316. URL: https://inria.hal.science/hal-04318526.

[16] S. Riffaud. 'Accurate and robust predictions for model order reduction via an adaptive, hybrid FOM/ROM approach'. In: *Journal of Computational Physics* 523 (2024), p. 113677. DOI: 10.1016/j.jcp.2024.113677. URL: https://inria.hal.science/hal-04361506.

[17] S. Riffaud, M. A. Fernández and D. Lombardi. 'A low-rank solver for parameter estimation and uncertainty quantification in linear time dependent systems of Partial Differential Equations'. In: *Journal of Scientific Computing* 99.2 (2024), p. 34. DOI: 10.1007/s10915-024-02488-3. URL: https://inria.hal.science/hal-03908682.

Doctoral dissertations and habilitation theses

[18] D. Corti. 'Numerical methods for immersed fluid-structure interaction with enhanced interfacial mass conservation'. Sorbonne Université, 27th June 2024. URL: https://inria.hal.science/tel-04632496.

[19] S. C. Faya. 'Modeling and numerical simulation applied to the prediction of the effect of drugs in the cardiovascular system'. INRIA, 16th Dec. 2024. URL: https://theses.hal.science/tel-04849738.

[20] F. Lespagnol. 'A new computational approach for fluid-structure interaction of slender bodies immersed in three-dimensional flows'. Politecnico di Milano. Dipartimento di mathematica (Milano, Italie); Sorbonne Université - Laboratoire Jacques-Louis Lions, 26th June 2024. URL: https://hal.science/tel-04660387.

[21] H. Liu. 'Empowering Predictivity and Speed of hiPSC CM Assays by Machine Learning Approach'. Sorbonne Université, 2nd May 2024. URL: https://theses.hal.science/tel-04573685.

Reports & preprints

[22] R. Araya and M. A. Fernández. *Fractional-step methods and PSPG stabilized finite elements for the transient Stokes equations*. 28th June 2024. URL: https://hal.science/hal-04629064 (cit. on p. 12).

[23] M. Barré, C. Grandmont and P. Moireau. *A projection scheme for an incompressible soft material poromechanics model*. 25th June 2024. URL: https://inria.hal.science/hal-04624329 (cit. on p. 10).

[24] M. Boulakia, C. James and D. Lombardi. *Numerical approximation of the unique continuation problem enriched by a database for the Stokes equations*. 4th Oct. 2024. URL: https://inria.hal.science/hal-04721560 (cit. on p. 11).

[25] E. Burman, G. Delay and A. Ern. *The unique continuation problem for the wave equation discretized with a high-order space-time nonconforming method*. 19th July 2024. DOI: 10.1137/22M1508637. URL: https://hal.science/hal-04654228 (cit. on p. 12).

[26] D. Corti, J. Diaz, M. Vidrascu, D. Chapelle, P. Moireau and M. A. Fernández. *A fictitious domain method with enhanced interfacial mass conservation for immersed FSI with thin-walled solids*. 28th Sept. 2024. URL: https://hal.science/hal-04713023 (cit. on p. 11).

[27] S. C. Faya, W. Callan, M. Vidrascu, M. A. Fernández, P.-J. Guns and D. Lombardi. *Validation of a mathematical model of arterial wall mechanics with drug induced vasoconstriction against ex vivo measurements*. 19th Dec. 2024. URL: https://inria.hal.science/hal-04597238 (cit. on p. 10).

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