AEROSPACE ENGINEERING / ARCHITECTURAL, URBAN AND INTERIOR DESIGN / ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING / BIOENGINEERING / DATA ANALYTICS AND DECISION SCIENCES / DESIGN / ELECTRICAL ENGINEERING / ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY / ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING / INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING / INFORMATION TECHNOLOGY / MANAGEMENT ENGINEERING / MATERIALS ENGINEERING / **MATHEMATICAL MODELS AND METHODS IN ENGINEERING** / MECHANICAL ENGINEERING / PHYSICS / PRESERVATION OF THE ARCHITECTURAL HERITAGE / STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING / URBAN PLANNING, DESIGN AND POLICY

PhD Yearbook | 2022

PHD COURSE IN MATHEMATICAL MODELS AND METHODS IN ENGINEERING

Prof. Michele Correggi

Mathematics is everywhere, represented by equations. Between the atmosphere and the wing of a spaceship, in the blood flowing in an artery, on the demarcation line between ice and water at the poles, in the motion of the tides, in the charge density of a semiconductor, in the compression algorithms of a signal sending images from outer space. The equations represent real problems. The Mathematical Engineer can see and understand the nature of these equations, and can develop models in order to understand their relevant qualities and solve real problems.
This PhD program aims at training young researchers by providing them with a strong mathematical background and with ability to apply their knowledge to the solution of real-world problems that arise in various areas of science, technology, industry, finance, management, whenever advanced methods are required in analysis, design, planning, decision and control activities. PhD students carry out their research both in the development of new mathematical methods and in the implementation and improvement of advanced techniques in connection with specific contexts and applications.
The Faculty of the PhD program is responsible for the organization of the training and research activities of the PhD students. Decisions of the Faculty comply with the requirements and standards of the Doctoral School of the Politecnico di Milano. A Chairman is elected within the Faculty, for representative and coordination activities. Admission of students to the PhD program is decided after examination of the candidates. Students applying to our program must provide their CV, along with reference and motivation letters. After admission, each student is assigned a tutor. The tutor is a member of the Faculty who assists the student in the early stages of his career, especially in the choice of the courses and in identifying a thesis advisor.

The PhD program has a duration of three years. Activities include:
Soft skills courses; specialized courses; research training, including seminars, tutoring activity, participation to workshops/conferences, and scientific publications; development of a doctoral thesis.
At the end of each academic year, the PhD students report to the Faculty about their activity. The students report about attendance of courses and exams (and the corresponding grades), participation in various scientific activities (seminars, conferences, summer schools etc.), planning and intermediate results on their research project and preparation of the PhD thesis, and any other relevant activity. At the annual meeting the students also receive a grade by the Faculty. A negative grade may entail repetition of the current year of doctoral study (with suspension of the grant, if any) or exclusion from the PhD program, depending on the Faculty's decision. Mobility of PhD students to other institutions is strongly encouraged and financial support is provided to this purpose.

Among others, let us mention some typical types of professional skills and possible occupations of the graduated Doctors: analytic and numerical treatment of differential models for physical and industrial problems, quantitative methods in finance and risk management, operations research and optimisation, statistical modelling and data analysis.

Placement of graduated Doctors is expected in the following positions: research and development divisions of businesses, businesses involved in innovative design activities, financial institutions such as banks or insurance companies, public or private research centres, public and/or governmental agencies for social, economical, scientific study, planning or evaluation, Universities.
Since the PhD program in Mathematical Models and Methods in Engineering (formerly, Mathematical Engineering) has been active since the year 2001, we expect that a larger number of institutions and businesses will soon become more and more aware of the professional skills and expertise of graduated doctors.

Grants funded by external partners:
IIT, Leonardo Spa

ADVISORY BOARD
Bianchetti Marco – Intesa San Paolo
Chiaromonte Francesca – Scuola Superiore Sant'Anna
Decuzzi Paolo – Laboratory of Nanotechnology for Precision Medicine Department of Drug Discovery and Development Italian Institute of Technology
Mauri Aurelio – Micron
Ruffo Paolo – ENI S.p.A.

FACULTY BOARD
Prof. Correggi Michele
Prof. Antonietti Paola Francesca
Prof. Catino Giovanni
Prof. Ciarletta Pasquale
Prof. Confortola Fulvia
Prof.ssa Conti Monica
Prof. Fagnola Franco
Prof. Formaggia Luca
Prof. Grillo Gabriele
Prof. Gazzola Filippo
Prof. Guglielmi Alessandra
Prof. Lella Paolo
Prof. Magli Giulio
Prof. Marazzina Daniele
Prof. Marchini Elsa Maria
Prof. Paganoni Anna Maria
Prof. Perotto Simona
Prof. Quarteroni Alfio
Prof. Rodaro Emanuele
Prof. Sabadini Irene Maria
Prof. Sacco Riccardo
Prof. Sangalli Laura
Prof. Sgarra Carlo
Prof. Verani Marco
Prof. Verzini Gianmaria
Prof. Zunino Paolo

ADDITIVE NORMAL TEMPERED STABLE PROCESS: A NEW WAY TO MODEL THE IMPLIED VOLATILITY SURFACE

Michele Azzone - Supervisor: Prof. Roberto Baviera

In the thesis, we introduce a new class of pure jump additive processes for modeling equity implied volatility surfaces: the additive normal tempered stable process (ATS). We derive its short-time-to-maturity asymptotics. We show that ATS accurately calibrate the volatility level and skew on different days (nine -year dataset).
This framework allows pricing European options with classical closed-form methods (e.g., Lewis formula), on the one hand, and exotic derivatives with fast Monte Carlo schemes, on the other hand. The ATS is a simple additive process for equity index derivatives. A process is said to be an additive process if it presents independent (but not-stationary) increments. In particular, we present in detail the application of Normal Tempered Stable processes (e.g., NIG and VG) with time-dependent parameters. It accurately fits the equity index volatility surfaces in the whole time range of quoted instruments, including options with small time-horizon (days) and long time-horizon (years). We introduce the model via its characteristic function; this allows using Fourier pricing techniques. We show that even if the model loses the classical stationarity property of Lévy processes, it presents interesting scaling properties for the calibrated parameters. The two power-law scaling parameters are beta, related to the variance of jumps, and delta related to the smile asymmetry.
In option market data, we observe that beta=1 and delta=-1/2; we build a statistical test that confirms this power-law scaling result.
We examine the short-time-to-maturity behavior of the ATS. As emphasized by empirical studies, a negative skew inversely proportional to the square root of the time-to-maturity characterizes the equity implied volatility. We prove that the implied volatility of these additive processes is consistent, in the short time, with the equity market observed characteristics if and only if beta=1 and delta=-1/2.
We design a new fast Monte Carlo scheme also for ATS. The scheme leverages on the independence of the increments for additive processes and is based on the ATS characteristic function. We prove some bounds on the method biases and we test its performances against a classic Gaussian approximation method (based on the ATS Lévy measure).
Finally, we test the quality of the calibration on historical S&P 500 and EURO STOXX 50 options prices on a large dataset composed by nine years of closing prices. To calibrate the process on equity market data, we introduce a new technique to recover the implicit discount factor (and forward prices) in the derivative market using only European put and call prices: this discount is grounded in actual transactions in active markets. The (unique) forward contract -built using the put-call parity relation- contains information about the market discount factor: by no-arbitrage conditions, we identify the implicit interest rate such that the forward contract value does not depend on the strike.

EFFICIENT REDUCED ORDER MODELING FOR NONLINEAR PARAMETERIZED PROBLEMS IN ELASTODYNAMICS: APPLICATION TO CARDIAC MECHANICS

Ludovica Cicci - Supervisor: Prof. Alfio Quarteroni - Co-Supervisor: Prof. Andrea Manzoni

In this Thesis we propose new computationally efficient solutions to nonlinear, parameterized time-dependent problems by means of reduced order models (ROMs). More specifically, we propose fast and accurate approximations of elastodynamics problems arising in cardiac mechanics. Being able to perform efficient numerical simulations in this context is indeed essential to explore multiple virtual scenarios, to quantify cardiac outputs and related uncertainties, as well as to evaluate the impact of pathological conditions. All these tasks call for repeated model evaluations over different input parameter values, thus making usual high-fidelity, full order models, such as those based on the finite element method, computationally prohibitive. Alternative numerical methods have been developed aiming to compute reliable solutions to parametric partial differential equations (PDEs) at a greatly reduced computational cost. Among these, the reduced basis (RB) method represents a powerful and widely used technique, characterized by a Galerkin projection of the problem onto a low-dimensional subspace and by a splitting of the reduction procedure into a costly offline phase and an inexpensive online phase. However, in the case of nonlinear problems, the online stage has a cost that still depends on the high-fidelity dimension, as the assembling of the reduced operators requires the reconstruction of the high-fidelity ones. In this Thesis we exploit the RB method, equipped with hyper-reduction techniques for handling the nonlinear terms, for the solution to time-dependent problems arising in cardiac mechanics, where the complex material behavior (the cardiac tissue) is described by means of an exponentially nonlinear constitutive law accounting for the presence of myocardial fibers. Some examples related to the use of hyper-ROMs in the multi-query contexts of sensitivity analysis and parameter estimation are also given. Nonetheless, severe challenges arise from the approximation of the nonlinear terms, usually requiring a large number of basis functions to correctly capture their variability, thus compromising the overall online efficiency of the ROM. To overcome the computational bottleneck of hyper-ROMs, we develop a novel projection-based, deep learning-based, ROM, that we name Deep-HyROMnet. The key idea is to combine the Galerkin-RB approach with deep neural networks (DNNs) to approximate reduced nonlinear operators efficiently. Unlike data-driven strategies, for which the predicted output is not guaranteed to satisfy the underlying PDE, Deep-HyROMnet is a physics-based ROM, as it computes the problem solution by solving a reduced nonlinear system. A further benefit of the proposed method lies on the fact that the inputs given to the DNNs are low-dimensional arrays, so that overwhelming training times and costs can be avoided. We show how our model outperforms classical hyper-ROMs (such as POD-Galerkin-DEIM ROMs exploiting the discrete empirical interpolation method) in terms of computational speed-up for the solution of a wide range of problems in nonlinear elastodynamics, still achieving accurate results. Finally, we demonstrate the performances of Deep-HyROMnet on patient-specific cardiac geometries involving about 127000 structural degrees of freedom, and consider the case of a 3D mechanics model that is monolithically coupled to a 0D windkessel model for blood circulation, to simulate the cardiac functions in both physiological and pathological scenarios.

NUMERICAL SOLUTION OF FLUID-STRUCTURE INTERACTION ARISING IN BLOOD PUMPS BASED ON WAVE MEMBRANES

Marco Martinolli - Supervisor: Prof. Christian Vergara

As the prevalence of heart failure continues to rise over time with aging of the population, *Left Ventricular Assist Devices* (LVADs) are life-sustaining therapeutic options that offer mechanical circulatory support in end-stage patients. The state of the art in the LVAD field is represented by *Rotary Blood Pumps*, whose functioning is based on the rotation of an internal impeller that imparts kinetic energy to the blood. A new frontier in the LVAD applications is represented by *Wave Membrane Blood Pumps* (WMBPs), developed at CorWave SA (Paris), in which blood propulsion arises from the progressive wave propagation along an oscillating immersed membrane (see Figure 1). The innovative technology of WMBPs has the potential to restore a physiologic pulsatile flow, while exerting lower stress conditions on blood cells than modern RBPs.

The main purpose of this thesis is to numerically investigate the fluid-structure interaction between the blood and the elastic wave membrane via three-dimensional simulations in the real pump domain to better understand the physical principle in WMBPs and predict the pump perforamance, both in terms of hydraulic power and device hemocompatibility.
The adopted numerical strategy is based on the *Extended Finite Element Method* (XFEM), which is an unfitted mesh technique that avoids potential remeshing by using a fixed background mesh for the fluid problem. A *Discontinuous Galerkin* (DG) mortaring is applied at the fluid-structure interface, to couple the fluid and solid solutions. Furthermore, a relaxed penalized contact model was introduced to handle potential collisions between the oscillating membrane and the housing walls of the pump, in case of high wave undulations. Thus, we solved a time-dependent *Fluid-Structure-Contact Interaction* (FSCI) problem using the LIFEV library.

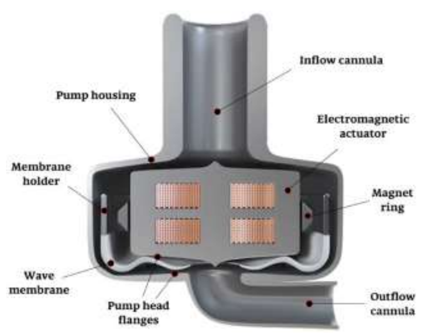

Fig. 1
Cross-sectional view of the Wave Membra Blood Pump structure.

The computational study was conducted in two different WMBP designs, the flat membrane pump design and the J-shape membrane pump design.
In both cases, the numerical solution was successfully validated against *in-vitro* experimental data (see Figure 2). In particular, we observed that, at identical operating conditions, the J-shape pump design outperformed the flat design. The numerical results highlighted the role of the membrane wave deformation in the transportation of fluid pockets against an adverse pressure gradient, ultimately resulting in the generation of positive blood flow at the pump outlet. Moreover, as the wave membrane comes close to contact with the pump walls, it prevents potential backflows from the outlet to the inlet.
The WMBP system was also simulated for different operating conditions,

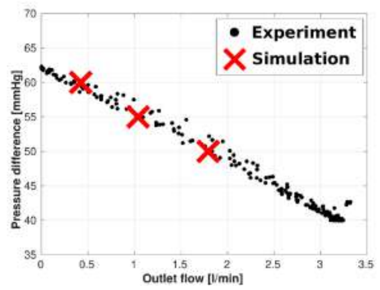

Fig. 2
Model validation of numerical results comparing pressure-flow rate experiment and simulation results.

varying pressure conditions, or frequency and amplitude of the membrane vibrations. In particular, the predicted hydraulic output of WMBPs increased when either the frequency or the amplitude of membrane oscillations were higher. We also observed limited hydrodynamic-generated shear stresses, suggesting good hemocompatibility properties of the WMBP system. Indeed, the values of blood Von Mises-like stress never exceeded reference thresholds found in literature for hemolysis or thrombosis, which are the two most common hemocompatibility-related adverse events. Additionally, no recirculation or stagnation areas were identified in the flow field, furtherly indicating a reduced possibility of inside-pump thrombogenesis.

Taking advantage of the insight of this parametric analysis, we tested a new operating point in the more recent J-shape design, considering higher amplitudes for the membrane oscillation. This novel operating, called *nominal opearating point*, achieved physiologic flow rate target of 6.5 L/min at typical diastolic head pressure for a failed heart. Indeed, in this case, the increased amplitude parameter allowed for a more effective wave membrane propagation and, consequently, for a better fluid pocket propagation towards the outlet channel (see Figure 3).

Finally, a preliminary study over the secondary non axi-symmetric modes of membrane vibration was presented, taking full advantage of the three-dimensional nature of the computational simulations. Indeed, we observed non axi-symmetric patterns in the membrane deformation for specific operating conditions of the device, confirming the experimental evidences obtained with laser profile tests. Nonetheless, a more in-depth investigation is needed to understand the origin of these secondary modes and determine their effect on the general device performance.

In conclusion, the proposed fluid-structure-contact model proved to be a reliable tool to predict the performance of WMBPs at different working conditions and support pump development in view of its application in the upcoming first-in-human trials.

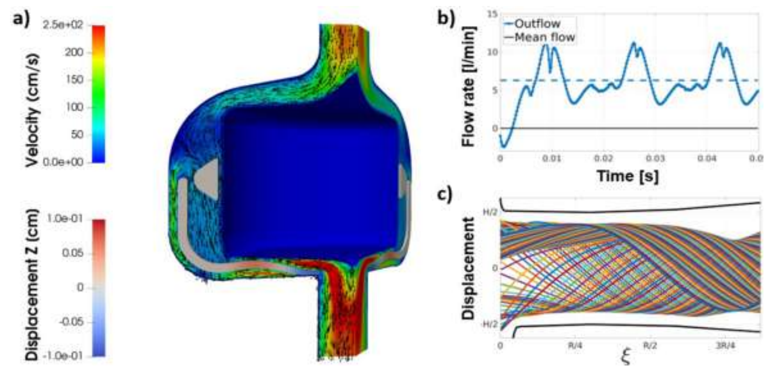

Fig. 3
Simulation results at nominal operating point.
a) Velocity and displacemente field. b) Outlet flow rate in time.
c) Membrane midline envelope.

NONLINEAR PARABOLIC DIFFERENTIAL EQUATIONS: GLOBAL EXISTENCE AND BLOW UP OF SOLUTIONS

Giulia Meglioli - Supervision Prof. Fabio Punzo

The main topic of this thesis concerns the study of global existence and blow-up of solutions to certain nonlinear parabolic differential equations. The thesis is divided into three parts where three different equations are considered. In Part I, we analyze the Cauchy problem for the porous medium equation with a variable density, which is a function of the space variable, and a power-like reaction term. This differential equation has been introduced as a mathematical model of evolution of plasma temperature where the density of the particle varies in space and the reaction term represents the volumetric heating of plasma. Depending on the rate of decaying at infinity of the density function, by comparison method and suitable sub- and supersolutions, we determine whether the solution exists globally in time or blows up in finite time. In Part II, we consider reaction-diffusion equations posed on complete, noncompact, Riemannian manifolds of infinite volume. Such equations contain power-type nonlinearity and slow diffusion of the porous medium type. It is well known that this kind of equations model a large variety of physical phenomenon such as the flow of a gas through a porous medium, the groundwater flow, the nonlinear heat transfer and population dynamics. Furthermore, we point out that it is quite natural to consider these equations posed on a Riemannian manifold if one wants to take into account the curvature of the underlying space where the physical phenomenon takes place. For the Cauchy problem of the latter equation, we prove global existence for positive initial data belonging to suitable L^p spaces, and that solutions corresponding to such data are bounded at all positive times with a quantitative bound on their L^∞ norm. The methods of proof are functional analytic in character, as they depend solely on the validity of the Sobolev and of the Poincaré inequalities. In Part III, we are concerned with nonexistence results for a class of quasilinear parabolic differential equations with a potential in bounded domains. In particular, we investigate how the behavior of the potential near the boundary of the domain and the power nonlinearity affect the nonexistence of solutions.

MATHEMATICAL AND NUMERICAL MODELING OF CARDIAC FIBER GENERATION AND ELECTROMECHANICAL FUNCTION: TOWARDS A REALISTIC SIMULATION OF THE WHOLE HEART

Roberto Piersanti - Supervisor: Prof. Alfio Quarteroni

Cardiovascular diseases are the primary cause of mortality worldwide, affecting millions of people every years. Although advancements in medical practice are continuously improving the diagnosis and treatment techniques, computer-based simulations of the cardiac function are gradually becoming a powerful tool to better understand the heart function and to support clinical decision-making. Even though some area of heart modeling reached a certain level of maturity, whole heart models are a far-reaching endeavour and are still in their infancy.
This thesis provides a detailed fully coupled multiscale mathematical and numerical model of cardiac electromechanics (EM) of the whole human heart. Two crucial factors for accurate numerical simulations of cardiac EM, which are also essential to reproduce the synchronous activity of the heart, are: reconstructing the muscular fiber architecture, that drives the electrophysiology signal and the myocardium contraction; accounting for the interaction between the heart and the circulatory system, that determines pressures and volumes loads in the heart chambers. With the aim of facing the challenges formerly described, the main contributions in this thesis move along two strands. On the one hand, we developed a unified mathematical framework, based on Laplace-Dirichlet-Rule-Based-Methods (LDRBMs), to prescribe myocardial fibers orientation in computational four chamber heart geometries. On the other hand, we provide a biophysically detailed cardiac 3D EM model coupled with a 0D closed-loop lumped parameters model for the haemodynamic of the whole circulatory system.
The whole heart fiber architecture is built upon a new LDRBM, a RBM strictly related to the solution of Laplace boundary-value problems. The latter is based on the novel definition of several inter-heart and intra-heart harmonic functions, which couple together the atria and the ventricles. To properly reproduce the characteristic features of the cardiac fiber bundles in all the four chambers, the heart LDRBM uses the gradient of inter-heart and intra-heart harmonic functions combined with a precise definition of the boundary sections, where boundary conditions are prescribed for the harmonic problems. The proposed methodology was demonstrated to quantitatively replicate the complex arrangement of the fiber directions in almost every anatomical cardiac region, see Figure 1(a). The heart LDRBM is computationally inexpensive, easy to implement, and it allows to include realistic cardiac muscle fibers architecture on whole heart geometries of arbitrary shape. Therefore, it is possible to generate patient specific heart fibers, fed by input parameters inferred from histology or DT-MRI studies, through an automated and computationally efficient procedure.
Apart from a very detailed myocardial fiber architecture, the whole heart model of this thesis considers a 3D description of cardiac EM in all the four chambers and a 0D representation of the circulatory system, which includes the cardiac blood haemodynamic, see Figure 1(b). The 3D EM part comprises: the cardiac electrophysiology (EP), described by means of the monodomain equation endowed with state of the art human ionic models for the ventricle and the atria; the sarcomere mechanical activation, based on an Artificial Neural Network model, which is able to represent in detail the sophisticated microscopic active force generation mechanisms; the myocardial tissue mechanic, for both the atria and the ventricles, represented adopting an orthotropic active stress formulation, which surrogates the contraction caused by dispersed myofibers.
The whole heart EM model is strongly coupled with a 0D closed-loop lamped parameters model for the blood haemodynamic through the entire cardiovascular network, where systemic and pulmonary circulations are modelled with RLC circuits and non-ideal diodes stand for the heart valves. The coupling between the 0D-fluid and 3D-EM models is achieved by means of the volume-consistency coupling conditions, where the pressures of all the four chambers act as Lagrange multipliers associated to the volume constraints.
The numerical approximation of the 3D-0D heart model included: finite Element Method (FEM) with continuous FE and hexahedral meshes, for the space discretization, and finite difference schemes with backward difference formulae, for the time discretization. The Segregated-Intergrid-Staggered numerical scheme was adopted. The core models, contributing to both cardiac EM and blood circulation, are solved sequentially once per time step in a segregated manner, by using different resolutions in space and time, to properly handle the heterogeneous space-time scales of the core models.
The validity of the whole heart 3D-0D model was demonstrated through EM simulations, see Figure 1(c), with physiological activation sites in a four-chamber realistic computational domain of the Zygote heart, a CAD-model representing an average healthy human heart reconstructed from high-resolution CT-scan. EM simulations of the whole heart produced a physiologically compatible timing for the cardiac activation in accordance with previous reports. Moreover, some relevant mechanical biomarkers, obtained by numerical simulations, are compared with those provided by the data reported in the literature. All the mechanical biomarkers fall within the physiological range.
Systematic comparisons of LDRBMs are carried out in terms of meaningful electrophysiological and mechanical biomarkers computed as output of numerical simulations. The effect of different configurations in cross-fiber active contraction, that surrogate the myofibers dispersion, was investigated in EM simulations. Furthermore, the results of the novel LDRBM were compared with the fiber orientations obtained by another RBM and to anatomical and DT-MRI fiber data.
The proposed 3D-0D whole heart model, presented in this thesis, provides an important contribution to the whole heart modeling and to perform full heart EM simulations, allowing both the study of four chamber s heart clinical cases as well as investigating medical questions.

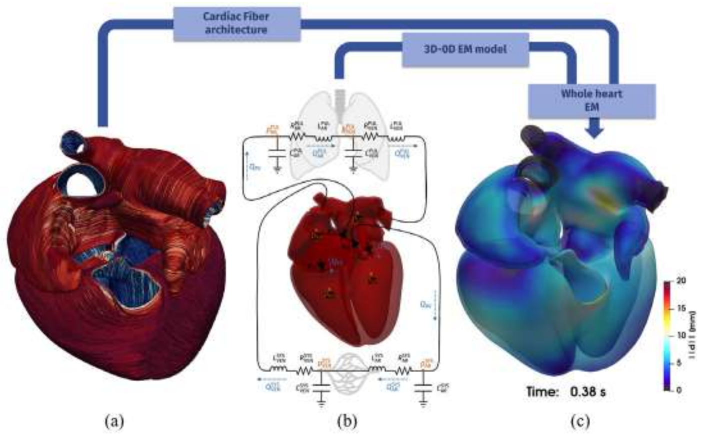

Fig. 1
a) cardiac fiber architecture; b) 3D-0D whole heart model; c) full heart EM simulation.

MATHEMATICAL AND NUMERICAL MODELING OF CARDIAC ELECTROMECHANICS IN VENTRICLES WITH ISCHEMIC CARDIOMYOPATHY

Matteo Salvador - Supervisor Prof. Alfio Maria Quarteroni - Co- Supervisor: Prof. Luca Dede'

The cardiac function is the result of the concerted action of several physical phenomena, ranging from the cellular scale to the organ level. Among these, an important role is played by the coupling between the electrical activity of the heart and its mechanical contraction. For this reason, numerical simulations of ventricular electromechanics play nowadays a crucial role in computational cardiology and precision medicine. Indeed, it is of outmost importance to analyze and better address pathological conditions by means of anatomically accurate and biophysically detailed individualized computational models that embrace electrophysiology, mechanics and hemodynamics.
In this thesis, we develop a novel electromechanical model for the human ventricles of patients affected by ischemic cardiomyopathy. This is made possible thanks to the introduction of a spatially heterogeneous coefficient that accounts for the presence of scars, grey zones and non-remodeled regions of the myocardium. We couple this 3D electromechanical model with either a 2-element windkessel afterload model or a 0D closed-loop circulation model by an approach that is energy preserving. Our mathematical framework keeps into account the effects of mechano-electric feedbacks, which model how mechanical stimuli are transduced into electrical signals. Moreover, it permits to classify the hemodynamic nature of tachycardias. These aspects are very important for the clinical exploitation of our electromechanical model.
We propose two segregated-intergrid-staggered (SIS) numerical schemes to solve this 3D-0D coupled problem. Specifically, we consider two partitioned strategies for which different space-time resolutions are employed according to the specific core model. In particular, numerical models for cardiac electrophysiology require a finer representation of the computational domain and a smaller time step than those used for cardiac mechanics. For the first numerical scheme (SIS1), we introduce intergrid transfer operators based on Rescaled Localized Radial Basis Functions to accurately and efficiently exchange information among the Partial Differential Equations (PDEs) of the electromechanical model. Different (potentially non-nested) meshes and first-order Finite Elements can be used for the space discretization of the PDEs. The second numerical scheme (SIS2) that we propose employs another flexible and scalable intergrid transfer operator, which allows to interpolate Finite Element functions between nested meshes and, possibly, among arbitrary Finite Element spaces for the different core models.
We perform numerical simulations both in sinus rhythm and ventricular tachycardia for different scenarios of clinical interest.
We also design a Machine Learning method to perform real-time numerical simulations of cardiac electromechanics. Our method allows to derive a reduced-order model (ROM), written as a system of Ordinary Differential Equations, in which the right-hand side is represented by an Artificial Neural Network (ANN), that possibly depends on a set of parameters associated with the model to be surrogated. This method is non-intrusive, as it only requires a collection of pressure and volume transients obtained from the full-order model (FOM). Once trained, the ANN-based ROM can be coupled with hemodynamic models for the blood circulation external to the heart, in the same manner as the original electromechanical model, but at a dramatically reduced computational cost. We demonstrate the effectiveness of the proposed strategy on two relevant contexts in cardiac modeling. We employ the ANN-based ROM to perform a global sensitivity analysis on both the electromechanical and the hemodynamic models. Then, we perform a Bayesian estimation of a couple of parameters starting from noisy measurements of two scalar outputs.
By replacing the FOM of cardiac electromechanics with the ANN-based ROM, we perform in a few hours of computational time all the numerical simulations, which would be unaffordable, because of their overwhelming computational cost, if carried out with the FOM. As a matter of fact, our ANN-based ROM is able to speed up the numerical simulations by more than three orders of magnitude.

Fig. 1
Distribution of scars (black), grey zones (grey) and non-remodeled regions (red) over the myocardium for a patient-specific left ventricle with ischemic cardiomyopathy.

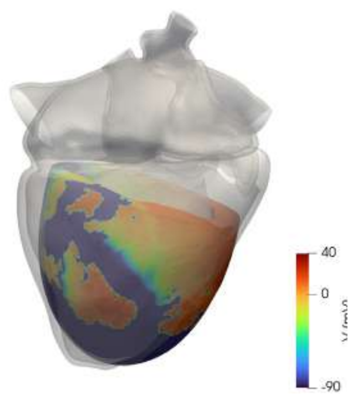

Fig. 2
Electromechanical simulation of ventricular tachycardia in a patient-specific case with ischemic cardiomyopathy.

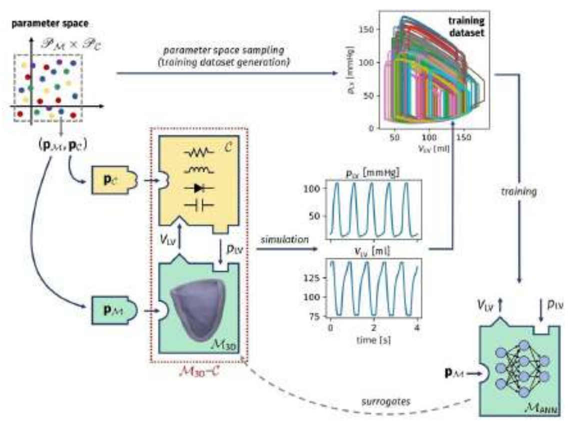

Fig. 3
Training algorithm for the Artificial Neural Network based reduced order model of cardiac electromechanics.

MATHEMATICAL AND NUMERICAL MODELS FOR THE FLUID DYNAMICS OF THE HUMAN HEART

Alberto Zingaro - Supervisor: Prof. Alfio Quarteroni - Co-Supervisor: Prof. Luca Dede'

Computer-based numerical simulations - also known as in silico simulations - of the heart and blood circulation represent a valuable tool to analyze the cardiac function and to enhance the understanding of cardiovascular diseases. In this thesis, we introduce a Computational Fluid Dynamics (CFD) model for the numerical simulation of the whole heart hemodynamics in both physiological and pathological conditions, by accounting for all the physical processes that influence cardiac flows: moving domain and interaction with electromechanics, transitional-turbulent flows, cardiac valves and coupling with the external circulation.

We propose a volume-based displacement model for the left atrium in physiological conditions and we simulate the atrial hemodynamics by considering both idealized and patient specific-geometries. A lumped-parameter (0D) closed-loop circulation model serves as input to provide the CFD simulations with flowrates, pressures and atrial displacement. We further extend the computational model to account for atrial fibrillation in patient-specific CFD simulations by devising a parametric displacement field. We investigate the effects of atrial fibrillation on the left atrium hemodynamics and we quantify an increasing blood stasis, especially in the left atrial appendage, where a dramatic washout reduction is observed.

The transitional blood flow regime is simulated by means of the Variational Multiscale - Large Eddy Simulation (VMS-LES) method, which acts as both a stabilization and a turbulence model. We investigate the role of the VMS-LES method in transitional hemodynamic flows by considering the atrial CFD simulation in physiological conditions: if relatively coarse meshes are used, numerical results suggest that the additional stabilization terms introduced by the VMS-LES method allow to better predict transitional effects and cycle-to-cycle blood flow variations than the standard Streamline Upwind Petrov Galerkin (SUPG) method. To enhance the accuracy of the stabilization methods, we propose a novel computational strategy based on Artificial Neural Networks (ANNs) to predict the optimal stabilization parameter. Numerical tests carried out on the SUPG method for advection-diffusion problems show that the ANNs-based approach leads to more accurate solutions than standard methods.

We simulate the hemodynamics of the left heart and we integrate the electromechanical activity in the CFD model by employing a 3D cardiac electromechanical model of the left ventricle coupled to a 0D circulation model. We propose a novel preprocessing procedure that combines the harmonic extension of the ventricular electromechanical displacement with the motion of the left atrium based on the 0D model. To better match the 3D CFD with the remaining blood circulation, we devise a coupled 3D-0D model made of the 3D CFD model of the left heart and the 0D circulation model: from a numerical point of view, we solve the coupled model by a segregated scheme, and we develop algorithms to solve the integrated system comprising fluid dynamics, displacement, valves and circulation models. Numerical simulations on a healthy left heart show that biomarkers and flow patterns are accurately reproduced when compared with in-vivo data; the flexibility of the model allows to simulate also pathological scenarios as mitral valve regurgitation. We then expand our computational model to the hemodynamics of the four heart chambers: the displacement field is computed through a biventricular electromechanical simulation and then extended on the whole heart following the same methodology proposed for the left part, finally bringing to an integrated multiscale CFD model of the whole human heart.

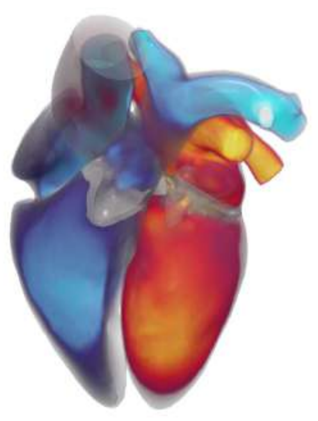

Fig. 1
Fluid dynamics of the whole heart during diastole.