INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Macs

Modeling, Analysis and Control for Computational Structural Dynamics

Paris - Rocquencourt

Theme : Observation, Modeling, and Control for Life Sciences

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1. Team

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2. Overall Objectives

2.1. Introduction

Numerical simulation has become a widespread tool in engineering. This fact is particularly noteworthy in the field of solid and structural mechanics which has given birth to finite element methods. In industrial design processes, experimenting and simulation go hand in hand, but the balance is increasingly shifted towards simulation, resulting into reduced costs and time to market.

In this general context, the objectives of the Macs project are to address new challenges arising from:

- the need to develop numerical procedures which are *reliable* and well-adapted to *industrial applications*;
- the emergence of *active mechanics* (e.g. control and optimisation) enabling the design of thinner and lighter (hence cheaper) structures, for which innovative modeling and discretization approaches are required.

These research directions benefit from a strong scientific environment and background at INRIA in the fields of numerical analysis and scientific computing (with a well-established record in structural mechanics), as well as in automatic control.

We also emphasize that – in the recent years – we have started to investigate some such issues more particularly related to biomechanical modeling.

2.2. Highlights of the year

- First “real life” clinical validations of cardiac modeling for medical decision-making, see Section 6.3.1;
- New “reduced-unscented” filtering methodology avoiding to compute tangent operators in nonlinear estimation problems, see Section 6.3.3 and [8].

3. Scientific Foundations

3.1. Formulation and analysis of effective and reliable shell elements

Thin structures (beams, plates, shells...) are widely considered in engineering applications. However, most experts agree that the corresponding discretization procedures (finite elements) are not yet sufficiently reliable, in particular as regards shell structures. A major cause of these difficulties lies in the numerical locking phenomena that arise in such formulations [1].

The expertise of the team in this area is internationally well-recognized, both in the mathematical and engineering communities. In particular, we have strongly contributed in analysing – and better explaining – the complex locking phenomena that arise in shell formulations [1]. In addition, we have proposed the first (and only to date) shell finite element procedure that circumvents locking [19]. However, the specific treatment applied to avoid locking in this procedure make it unable to correctly represent membrane-dominated behaviors of structures (namely, when locking is not to be expected). In fact, a "perfect shell element" – namely, with the desired reliability properties mathematically substantiated in a general framework – is still to be discovered, whereas numerous teams work on this issue throughout the world.

Another important (and related) issue that is considered in the team pertains to the design and analysis of numerical procedures that are adapted to industrial applications, i.e. that fulfill some actual industrial specifications. In particular, in the past we have achieved the first mathematical analysis of "general shell elements" – which are based on 3D variational formulations instead of shell models – these elements being among the most widely used and most effective shell elements in engineering practice.

3.2. Stability and control of structures

Stability of structures is – of course – a major concern for designers, in particular to ensure that a structure will not undergo poorly damped (or even unbounded) vibrations. In order to obtain improved stability properties – or to reach nominal specifications with a thinner a lighter design – a control device (whether active, semi-active, or passive) may be used.

The research performed in the team in this area – other than some prospective work on robust control – has been so far primarily focused on the stability of structures interacting with fluid flows. This problem has important applications e.g. in aeronautics (flutter of airplane wings), in civil engineering where the design of long-span bridges is now partly governed by wind effects, and in biomechanics (blood flows in arteries, for instance). Very roughly, the coupling between the structure and the flow can be described as follows: the structural displacements modify the geometry of the fluid domain, hence the fluid flow itself which in turn exerts an action on the structure. The effects of structural displacements on the fluid can be taken into account using ALE techniques, but the corresponding direct simulations are highly CPU-intensive, which makes stability analyses of such coupled problems very costly from a computational point of view. In this context a major objective of our work has been to formulate a simplified model of the fluid-structure interaction problem in order to allow computational assessments of stability at a reasonable cost.

3.3. Modeling and estimation in biomechanics

A keen interest in questions arising from the need to model biomechanical systems – and to discretize such problems – has always been present in the team since its creation. Our work in this field until now has been more specifically focused on the objectives related to our participation in the ICEMA ARC projects and in the CardioSense3D initiative (see Section 7.1.1), namely, to formulate a complete continuum mechanics model of a beating heart, and to confront – or "couple", in the terminology of the INRIA strategic plan – numerical simulations of the model with actual clinical data via a data assimilation procedure.

Our global approach in this framework thus aims at using measurements of the cardiac activity in order to identify the parameters and state of a global electromechanical heart model, hence to give access to quantities of interest for diagnosing electrical activation and mechanical contraction symptoms. The model we propose is based on a chemically-controlled constitutive law of cardiac myofibre mechanics consistent with the behavior of myosin molecular motors [17]. The resulting sarcomere dynamics is in agreement with the “sliding filament hypothesis” introduced by Huxley. This constitutive law has an electrical quantity as an input which can be independently modeled, considered as given (or measured) data, or as a parameter to be estimated.

4. Application Domains

4.1. Application domains

Our researches have natural applications in all sectors of the mechanical industry: car and naval industries; aeronautics and space; civil engineering; tires; MEMs and nanotechnologies...

We also actively seek new applications in biotechnologies, although of course the economy and structuring of this sector is not as developed yet.

5. Software

5.1. MODULEF

Participants: Dominique Chapelle, Marina Vidrascu [correspondant].

Most of the software developed in our team is integrated in the Modulef library. Modulef is designed to provide building blocks for effective and reliable software development in finite element analysis. Well-adapted rigorous data structures and ease of integration (for new methods or algorithms) are some of its key advantages. Until 1998, Modulef was distributed by the Simulog company within a club structure (for a membership fee). In order to encourage its dissemination, its status was then changed to make it freely available. It can be downloaded at no charge from the INRIA-Rocquencourt web site (http://www-rocq.inria.fr/modulef/).

5.2. OpenFEM: a Finite Element Toolbox for Matlab and Scilab

Participants: Dominique Chapelle [correspondant], Philippe Moireau, Marina Vidrascu.

OpenFEM (http://www.openfem.net) is an *opensource* finite element toolbox for linear and nonlinear structural mechanics within the Matlab and Scilab matrix computing environments. This software is developed in a collaboration between Macs and the SDTools company [1]. Performing finite element analyses within a matrix computing environment is of considerable interest, in particular as regards the ease of new developments, integration of external software, portability, postprocessing, etc. This rather young software is already quite successful in the finite element community (about 300 downloads per month).

5.3. MITCNL

Participants: Dominique Chapelle, Marina Vidrascu [correspondant].

The package MITCNL is a set of subroutines that implements the triangular MITC3, MITC6 and quadrilateral MITC4 and MITC9 shell elements for large displacements [1]. We use it as a basis for new developments of shell elements, in particular within Modulef. It can be easily interfaced with most finite element codes as well. We also license this package to some of our partners for use with their own codes.

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[1] http://www.sdtools.com

5.4. HeartLab

Participants: Dominique Chapelle, Radomir Chabiniok, Philippe Moireau [correspondant], Jacques Sainte-Marie.

The heartLab software is a library written in Matlab and C (mex functions) designed to perform both simulation and estimation (based on various types of measurements, e.g. images) of the heart mechanical behavior. Started in 2006, it is already quite large (about 30000 lines), and is used within the CardioSense3D community.

The code relies on OpenFEM for the finite element computations, and the implementation was performed with a particular concern for modularity, since modeling and estimation use the same finite element operators. This modularity also allows to couple the code with other FEM solvers, such as LifeV developed in the Reo team-project. In particular, we are now able to include perfusion and electrical coupling with LifeV using PVM.

We also included geometric data and tools in the code to define heart anatomical models compatible with the simulation requirements in terms of mesh quality, fiber direction data defined within each element, and referencing necessary for handling boundary conditions and estimation, in particular. These geometries are analytical or come from computerized tomography (CT) or magnetic resonance (MR) image data of humans or animals.

6. New Results

6.1. Modeling and simulation of fluid-structure interaction problems

6.1.1. Modeling of biological capsules

Participants: Marina Vidrascu, Dominique Chapelle.

This year we started a collaboration with Anne-Virginie Salsac and Johann Walter from UTC on a fluid-structure algorithm for capsules such as blood red cells. The group in Compiègne has intensively worked on the study of the deformation of a capsule in an external flow. This is a complex problem because it is necessary to take into account the fluid flows inside and outside the capsule as well as the dynamics of the membrane that has viscoelastic properties. As the numerical code is based on the surface integral method for the fluids, the fluid structure interaction algorithm used is very specific. Unlike the standard situation where the fluid problem is solved with Dirichlet boundary conditions and the solid problem with Neumann boundary conditions, here it is more convenient to do the opposite. Our collaboration consists in combining this algorithm with a solid solver based on robust shell elements. The first results are encouraging.

6.1.2. Cardiovascular fluid-structure interaction

Participants: Philippe Moireau, Dominique Chapelle.

The objective of P. Moireau's 8 months visit in the Cardiovascular Biomechanics Lab (CVBRL) of Charles Taylor in Stanford was to set up a full simulation of patient-specific fluid structure interaction (FSI) in arteries using an estimation procedure with real data. In close collaboration with Jean-Fédéric Gerbeau from Reo, Alberto Figueroa and Nan Xiao from CVBRL, we have improved the solid boundary condition of the FSI models developed at CVBRL and INRIA (Macs and Reo) in order to obtain more realistic simulations. More precisely, considering for instance the aorta, the main idea is to take into account surrounding organs either fixed – the spine – or mobile – the heart – by reducing them to accurate visco-elastic Robin conditions on part of the domain. These improvements were assessed in the context of a fluid structure simulation of a complete ascending aorta built from CT images and provided a much more accurate simulation compared with the reference image sequence. An article is in preparation on this subject.

However, this new modeling component must be adequately calibrated. And it is difficult to set up patient-specific values off-line since this is a simplified model. In this context, we have decided to use the parametric estimation procedure that we have developed for the heart in the past few years, especially the new tangent-free methodology published in [8] – see Section 6.3.3. Hence, we have implemented and tested this procedure to estimate the elastic part of the Robin condition allowing to detect the spine attachment on the aorta in a complete FSI simulation. The results obtained with synthetic data are excellent and we are in the process of seeking similar results with the real CT sequence.

6.2. Modeling and simulation of multi-layers mechanical structures

Participants: Dominique Chapelle, Michele Serpilli, Marina Vidrascu, Sofiene Hendili.

The collaboration with Françoise Krasucki and Giuseppe Geymonat (Montpellier University) on the modeling of 3D materials connected by stiff interfaces started last year and continues within the Epsilon ANR project (Domain decomposition and multi-scale computations of singularities in mechanical structures 7.1.2). During Michele Serpilli's postdoc we studied the behavior of two elastic bodies coupled by a strong thin material layer for which the asymptotic behavior can be analysed when the stiffness grows [16]. This problem is difficult to solve directly with 3D models because the thin layer requires a very fine mesh, and furthermore the difference in elastic coefficients induces numerical difficulties. Introducing a variational limit problem allows to substitute the thin layer with a "material surface" which – in this case – is modeled by a membrane. We focused on effective numerical methods to solve this problem. A specific membrane element was developed to model this material surface. We first developed a domain decomposition algorithm which considers 3 different sub-domains and successfully compared it to the direct solution of the problem. Then we generalized the Neumann-Neumann preconditioner for this particular decomposition. In this case we need an inverse of the operator in each sub-domain. As the membrane operator is not well-posed this approach is not very reliable when the behavior of the thin layer is not pure membrane. An alternative is to consider the energy of the thin layer as a particular boundary condition. In this case there are only two sub-domains in which the problems are well posed, hence a Neumann-Neumann preconditioner is more effective.

Another problem of interest – defined in the objectives of the Epsilon ANR project – is to consider an elastic plate with a thin layer B_ϵ of periodically distributed heterogeneities. The layer contains a large number of small circular inclusions with a diameter ρ_ϵ, and the distance between two heterogeneities is δ_ϵ. Various methodologies to obtain an asymptotic behavior will be studied from a theoretical and numerical point of view for both empty and rigid inclusions. This is part of the subject of Sofiene Hendili's PhD. This year, during the internship of Sofiene Hendili we completed a the first step which was to directly solve the problem in order to obtain a reference solution. As the number of degrees of freedom is very large, a domain decomposition method was necessary to solve the problem.

6.3. Modeling and estimation of the electromechanical behavior of the heart

6.3.1. Modeling

6.3.1.1. Validation with animal experiments

Participants: Radomir Chabiniok, Dominique Chapelle.

In collaboration with Hôpital Henri Mondor (J.F. Deux and A. Rahmouni from the Radiology Dpt. and Pierre-François Lesault from the Cardiology Dpt.) we designed a special animal experiment, with the following objectives:

- Validation of the 3D model of the physiological heart.
- Adjustment of the parameters of the model to simulate clinically relevant myocardial infarction at various stages.

The subjects (2 small farm pigs) were examined – by means of cardiac MRI and invasive measurements of pressures in the heart cavities and large vessels – and data acquired once in a baseline condition (physiological heart beat), and twice after creation of a myocardial infarction.

We set up subject-specific simulations of the heart beat at the various stages, namely, for the baseline (pre-infarct) cases and for the two post-infarct conditions. The physical parameters were first calibrated with the baseline data. Then we used the same parameters for the infarcted heart, except for the tissue properties in the infarcted regions. Just by decreasing the contractility and increasing the passive tissue stiffness in these parts of the myocardium, we obtained simulations in excellent agreement with the infarcted heart data, see Figure 1. We thus showed that the model is predictive with respect to changes of pressure and volume indicators and to the local kinematics as well.

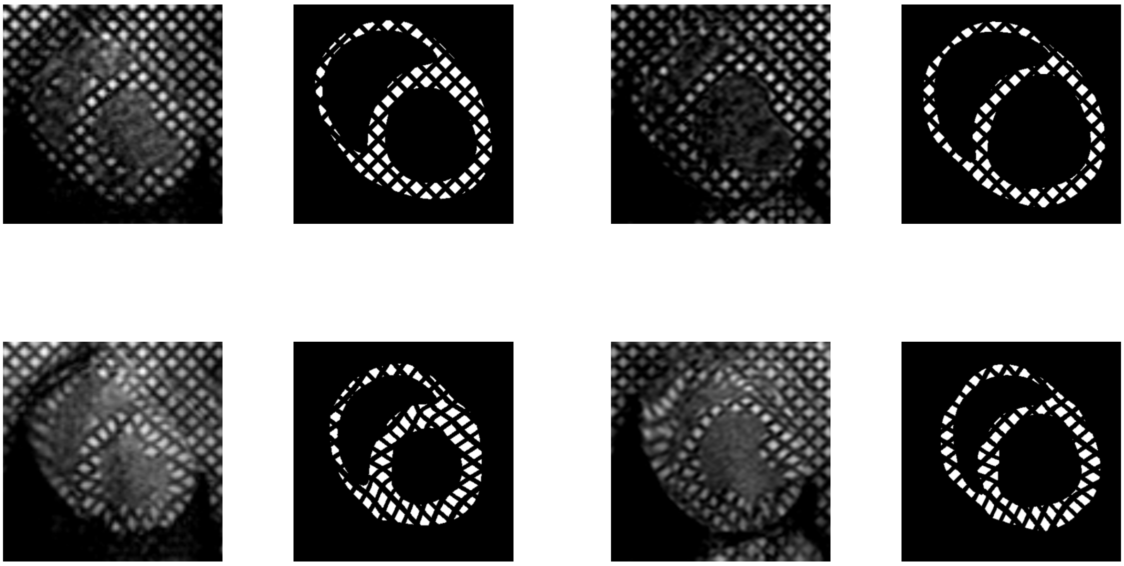

Figure 1. Comparison of MR and synthetic tagged images for baseline (left four images) and T0+10 stage (right four images). End-diastolic time frames are displayed in the upper row, end-systolic time frames in the lower row.

This work was presented at the MICCAI workshop on Cardiovascular interventional imaging and biophysical modeling in London in September 2009, see [11].

6.3.1.2. Clinical simulations of Cardiac Resynchronization Therapy (CRT)

Participants: Radomir Chabiniok, Dominique Chapelle.

In a collaboration with King's College London (KCL) and St. Thomas Hospital in London and project Asclepios of INRIA Sophia Antipolis, we started a pre-clinical validation of the model on a small group (8) of patients with severe heart failure. All the patients have a certain conduction system disorder (left bundle branch block - LBBB) and they are treated by cardiac resynchronization therapy (CRT). The objective is to investigate whether patient-specific heart models can accurately predict the impact of various resynchronization schemes, with the perspective of using such models to pre-operatively optimize the procedures.

A single case study was already presented at the FIMH 2009 conference [15]. The model parameters were calibrated with the baseline data, and then Figure 2 shows a comparison of simulated and measured pressure indicators for different electrical activation patterns, but of course without readjustment of the model parameters. This demonstrates an excellent predictive capability of the model. This investigation is still in progress with the other patients, and in the coming months we will also work on the automatic personalization (state and parameter estimation) of the models using the same datasets.

6.3.1.3. Poromechanics

Participants: Dominique Chapelle, Philippe Moireau, Jacques Sainte-Marie.

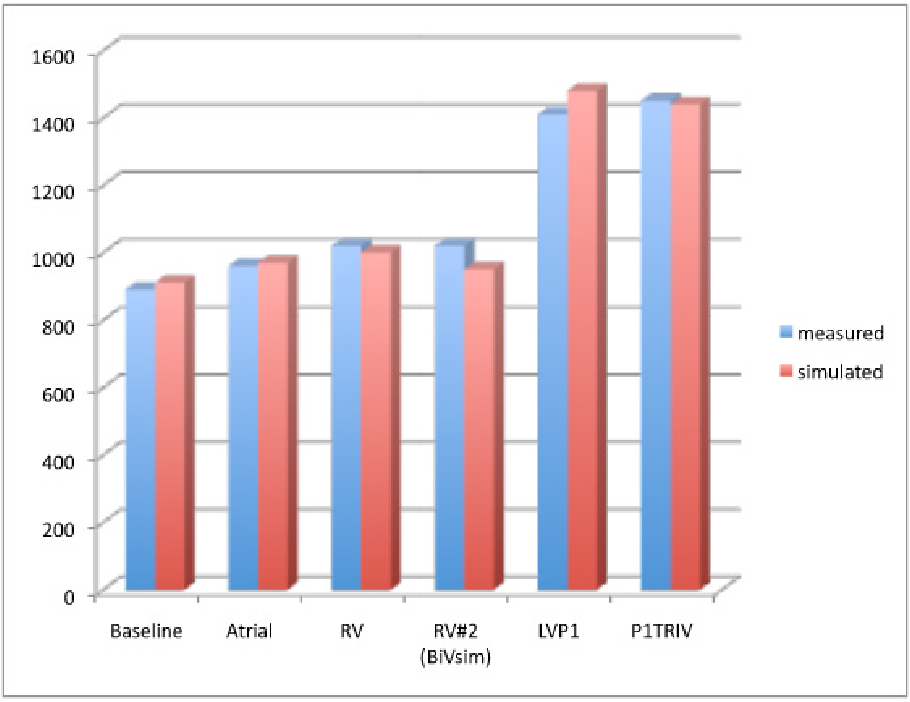

Figure 2. Comparison of simulated and measured pressure indicators for one patient with several activation patterns: dp/dt stands for time derivative of the LV pressure (a usual clinical indicator of LV contractility), ESV stands for end-systolic volume.

Poromechanics is a simplified mixture theory where a complex fluid-structure interaction problem is replaced by a superposition of both components, each of them representing a fraction of the complete material at every point. It originally emerged in soils mechanics. Finite strain poroelastic models have already been proposed, albeit with ad hoc formulations for which compatibility with thermodynamics laws and incompressibility conditions is not established.

The main contribution of this activity is the derivation of a general poroelastic model valid for a nearly incompressible medium which experiences finite deformations [18]. A numerical procedure is proposed to iteratively solve the porous flow and the nonlinear poroviscoelastic problems. Three-dimensional numerical experiments have been carried out to illustrate the model for typical poroelastic configurations: swelling and complete drainage. Simulations of cardiac perfusion have also been obtained in an idealized left ventricle embedded with active fibers. Results show the complex temporal and spatial interactions of the muscle and blood, reproducing several key phenomena observed in cardiac perfusion.

This study will be extended in four main directions:

- development of time discretization schemes compatible with thermodynamics principles;
- simulation of some characteristic pathologies, e.g. an infarcted area as reflected in a flow impediment combined with a decrease of local muscular contractility;
- modeling of the supply of the nutrients necessary for the cardiac muscle activity;
- validation and calibration with clinical data.

This work is carried out in collaboration with the REO team (I. Vignon-Clementel & J.F. Gerbeau). The Navier-Stokes and Darcy codes are developed in the LifeV platform [20] whereas for the simulation of the mechanical activity we use the HeartLab platform.

6.3.2. Model reduction

Participants: Dominique Chapelle, Asven Gariah, Jacques Sainte-Marie.

In biomechanical engineering, the simulations of 3D nonlinear models accounting for large strains and large displacements are costly, hence model reduction techniques are attractive.

Model reduction for nonlinear PDEs raises two main issues:

- the design of a reduced basis valid for significant variations of the initial conditions and/or the constitutive parameters of the model,
- the derivation of error estimates between the full simulation results and the reduced ones.

Unlike reduced basis techniques for which costly calculations are carried out *offline*, we are interested in POD (Proper Orthogonal Decomposition) type techniques, that have proved successful in domains ranging from signal analysis to fluid mechanics. Such techniques enable lighter and shorter *online* simulations of a PDE-based model, and rely on the knowledge of a few complete solutions, often called snapshots, that are supposed to capture the most “characteristic” behaviors of the system.

The POD method shows good reductibility and stability in the case of linear parabolic equations, especially its simplest form, the heat equation. We also explored the reduction properties of more complex systems of reaction-diffusion type (e.g. FitzHugh-Nagumo), which are nonlinear parabolic, parameter-sensitive and which exhibit a propagation-like behaviour. The usual POD criterion is inappropriate to conveniently reduce an interesting range of solutions and we have proposed extensions of the optimal criterion.

We are currently investigating the applications of POD methods on optimality systems and inverse problems with applications to the estimation of mechanical parameters arising in cardiac modeling. The aim is to make Kalman filtering type techniques tractable by reducing the size of the covariance matrices, in particular. This approach raises questions about reduced optimal control problems.

The main contributor on this subject is Asven Gariah whose PhD has begun in November 2008.

6.3.3. Estimation in cardiology

Participants: Dominique Chapelle, Philippe Moireau.

We have proposed in [8] a reduced-order version of the so-called Unscented Kalman Filter (UKF) which generalizes the principles presented in the original paper of [22]. Compared to our previous parametric estimator, this allows to employ a UKF filter to deal with parametric uncertainty, instead of EKF. The UKF method is much appreciated for its robustness and the fact that it avoids to compute tangent operators such as the derivative of the model with respect to parameters, by using only adequately-sampled "particle trajectories". The simplicity of implementation of this algorithm allows us to use it in various applications, including fluid-structure interaction in collaboration with the REO team-project. Therefore we have attacked the estimation problem of the elastic boundary condition model we have formulated (cf. section 6.1.2). The results are already very encouraging on synthetic data and we are proceeding to use this strategy for a complete aortic simulation based on a real geometry and functional data coming from CT imaging. From a theoretical point of view we are addressing the problem of observability of such problems when only the structure is observed.

6.4. Filtering for nonlinear hyperbolic systems

Participants: Marie-Odile Bristeau [BANG], Jacques Sainte-Marie.

For free surface flows modeling and more generally when dealing with conservation laws, the use of sequential filtering techniques gives additional source terms coming from the innovation residual and these source terms are difficult to discretize.

For the simulation and analysis of conservation laws (hyperbolic or not), the kinetic theory – by reducing the nonlinear PDE to a linear Boltzmann type transport equation – often allows to derive efficient numerical schemes. For sequential filtering techniques, we aim at formulating the innovation term under the form of a kinetic source term. This should allow to derive accurate and stable schemes preserving the equilibria, in particular. For topography source terms, such a *kinetic* formulation has been obtained by Simeoni [21].

These research activities dealing with the modeling of free surface flows and the coupling between hydrodynamics and biology are carried out in collaboration with the BANG team-project (M.-O. Bristeau and B. Perthame), and we refer to their activity report for the detailed description of the corresponding results and their dissemination.

The publications associated with this activity are [6], [9], [2].

6.5. Multi-scale modeling and simulation of rubber

Participants: Marina Vidrascu, Antoine Gloria [SIMPAF], Patrick Le Tallec [Ecole Polytechnique].

In collaboration with A. Gloria (project-team SIMPAF) and P. Le Tallec (Ecole Polytechnique), we are currently working on the implementation of a multiscale model for rubber based on the statistical physics description of a network of polymer chains. At the microscopic level the rubber is composed of a network of chains, for which the energy depends only on the average length of the chains. The macroscopic energy will be obtained by minimizing the energy of a representative sample of such chains for a linear deformation of the boundary. The numerical simulations are performed with the Modulef software. The sample of chains is obtained by meshing a stochastic set of points. Meshing tools from the Gamma project-team are used. The edges of the mesh represent the chains. In order to obtain the macroscopic energy, a non linear elasticity problem is solved on each stochastic mesh, and a specific finite element was designed to model the chains. The preliminary results show good properties for the energy obtained.

7. Other Grants and Activities

7.1. National projects

7.1.1. CardioSense3D

Participants: Radomir Chabiniok, Dominique Chapelle, Philippe Moireau, Marina Vidrascu.

CardioSense3D[2] is a 4-year Large Initiative Action launched in 2005 and funded by INRIA, which focuses on the modeling and estimation of the heart electro-mechanical behaviour. This action follows the 4-year ICEMA project. The core members of CardioSense3D are the INRIA project-teams Asclepios, Macs, Reo and Sysiphe, but other academic, industrial and clinical partners are closely associated in this action. See Section 6.3 for the detailed results obtained by Macs in this framework.

7.1.2. Epsilon

The Epsilon project is an ANR project entitled “Domain decomposition and multi-scale computations of singularities in mechanical structures”. The members are Institut d’Alembert at Paris 6, I3m at Montpellier, Laga at Paris-Nord and INRIA. INRIA is particularly involved in the modeling and simulation of an assembly of structures containing a very thin layer embedded in a 3D structure. Sofiene Hendili started his PhD (co-supervised by Montpellier and INRIA) on this subject in September.

7.2. International projects

7.2.1. euHeart

The euHeart Project[3] is a European FP7 project of the IP category. It combines seventeen industrial, clinical and academic partners, whose collective goal is the development of individualized, computer-based, human heart models. Using comprehensive, patient-specific data as the basis for their design, these models will provide insight into the origin and progression of specific disease patterns, including those associated with heart failure, heart rhythm disorders, coronary artery disease, and aortic disease.

Within this project, the Macs team is more specifically in charge of coordinating one workpackage entitled “Biophysical model personalisation”, which consists in developing some methodological and software tools to solve the inverse problems of concern in the applications considered in the project. In this framework we already organized a two days workshop in Paris in October to present some methodological guidelines and discuss the participants’ needs.

7.2.2. Other long-term collaborations

Collaboration on numerical locking with MIT and ADINA R&D (K.J. Bathe);

8. Dissemination

8.1. Various academic responsibilities

Dominique Chapelle:

- Vice-chairman of INRIA-Rocquencourt Project Committee (until August);
- Member of the editorial boards of “Computers & Structures” and “M2AN”;
- Elected member of the board of SMAI;
- Program committees of conferences FIMH, PICOF, and Maths A Venir 2009.

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

[3] http://www.euheart.eu/

8.2. Teaching activities

- Philippe Moireau: course “The Finite Element Method”, at ENSTA, Fall 2009.

8.3. Participation in conferences, workshops and seminars

Dominique Chapelle

- Conference SMAI’09, symposium “Optimal Control”, La Colle sur Loup, May 25–29, invited lecturer.
- Conference WC2009 (Biomedical Engineering World Congress), Münich, September 10th.
- Workshop “Control of Partial Differential Equations”, Paris, October 14–16, invited lecturer.
- Speaker at 40th anniversary workshop of “Laboratoire Jacques-Louis Lions”, December.
- Thesis defense opponent for Antti Niemi, Helsinki University of Technology, March 27th.

Radomir Chabiniok

- Speaker at MICCAI 2009, September 20-24, London, UK.
- Speaker at Conference of the Centre for research of cardiovascular diseases, October 19-21, Harrachov, Czech Republic.
- Nečas seminar on continuum mechanics, October 19, Charles University in Prague, Czech Republic.

Philippe Moireau

- Speaker at FIMH 2009 (Functional Imaging and Modeling of the Heart), Nice, June.
- Seminar at Compiègne University, December 8th.

Michele Serpilli

- Speaker at AIMETA congress, Ancona, Italy, September 14–17.

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Year Publications

Articles in International Peer-Reviewed Journal

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[7] P. MOIREAU, D. CHAPELLE, P. LE TALLEC. *Filtering for distributed mechanical systems using position measurements: Perspectives in medical imaging*, in "Inverse Problems", vol. 25, n° 3, 2009, 035010 (25pp), doi:10.1088/0266-5611/25/3/035010.

[8] P. MOIREAU, D. CHAPELLE. *Reduced-order Unscented Kalman Filtering with application to parameter identification in large-dimensional systems*, in "COCV", 2009, In Press.

[9] J. SAINTE-MARIE. *Vertically averaged models for the free surface Euler system. Derivation and kinetic interpretation.*, in "Mathematical Models and Methods in Applied Sciences (M3AS)", 2009, submitted.

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[10] E. AUDUSSE, M. BRISTEAU, J. SAINTE-MARIE. *Multilayer Saint-Venant System with Mass Exchanges*, in "Numerical approximations of hyperbolic systems with source terms, Castro-Urdiales", 2009.

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