INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Macs

Modeling, Analysis and Control for Computational Structural Dynamics

Rocquencourt

THEME NUM

Activity Report

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1. Team

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2. Overall Objectives

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.

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) finite element procedure that circumvents locking[1]. 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 and ICEMA2 ARC projects, 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.

[1] D. Chapelle and R. Stenberg. Stabilized finite element formulations for shells in a bending dominated state. *SIAM J. Numer. Anal.*, 36(1): 32-73, 1998.

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 activation and contraction symptoms. The model we propose is based on a chemically-controlled constitutive law of cardiac myofibre mechanics formulated in the Sosso project-team and consistent with the behavior of myosin molecular motors. 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 (see [2]), considered as given (or measured) data, or as a parameter to be estimated.

One of our key objectives in this prospective phase was also to survey – and investigate to some extent – the various difficulties to be faced in this global model-data coupling approach, in order to more precisely identify some fundamental (i.e. also going beyond the specific application at hand) research issues in which the team can make important contributions.

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; tyres; 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/), with about 100 downloads per month recorded.

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

Participants: Dominique Chapelle, Claire Delforge, Marina Vidrascu [correspondant].

OpenFEM (http://www.openfem.net) is an *opensource* toolbox for finite element analysis (presently for linear structural mechanics only) within the matrix computing environments Matlab and Scilab. This software is developed in a collaboration between Macs and the SDTools company [3]. It was originally developed for Matlab, and then a Scilab version was more recently produced as part of an “ODL” (which allowed to hire C. Delforge as junior technical staff for 2 years). 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). A pre-release of OpenFEM 2.0 (compatible with Scilab 3.0, in particular) is now available.

[2] Icema
[3] SDT

5.3. MITCNL

Participants: Dominique Chapelle [correspondant], Marina Vidrascu.

The package MITCNL is a set of subroutines that implements the 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.

5.4. Heart simulation package

Participants: Dominique Chapelle, Marina Vidrascu [correspondant].

In order to obtain simulations of the heart model that we have formulated (see Section 6.3) we developed this package based on OpenFEM and for use with Matlab. The Matlab environment allows powerful post-processing, ease of interfacing with other software (such as for simulating action potential propagation) and provides some very efficient solvers (e.g. UMFPACK).

6. New Results

6.1. Design and analysis of effective numerical procedures for structural mechanics

Keywords: *3D/shell coupling*, *MITC elements*, *numerical reliability*.

Participants: Dominique Chapelle, Iria Paris, Marina Vidrascu.

We have been working on the design of reliable *triangular* shell elements. This is a major applicative challenge, as existing triangular elements are well-known to be insufficiently reliable (especially as regards locking) whereas they are needed in many applications for which (unstructured) automatic mesh generation is used. This is the topic of I. Paris' PhD thesis. Numerical procedures have been implemented in order to assess tentative finite element schemes using carefully selected test problems. In addition we have designed a simple numerical test aimed at detecting membrane locking, which is the key difficulty in shell elements.

In addition, we have worked on developing new axisymmetric shell elements in the framework of our collaboration with Michelin, see Section 7.1.

6.2. Modeling and simulation of fluid-structure interaction problems

Keywords: *Newton algorithms*, *fluid-structure interaction*.

Participants: Patrick Le Tallec, Marina Vidrascu.

This work is done in collaboration with Jean-Frédéric Gerbeau[4]. The objective is to simulate the mechanical interaction between the blood and the wall of large arteries. Due to the so-called "added mass effect", this problem differs (physically and algorithmically) from other classical fluid-structure problems (aero-elasticity), as its stability strongly depends on the accuracy of the resolution of the fluid-structure coupling at each time step.

Specifically, this means that an accurate energy balance must be achieved at each time step, hence it is mandatory to solve the coupling by implicit schemas. The resulting non-linear fluid-structure problem is difficult to solve.

This year we validated the reliability of the coupled algorithm on rather realistic configurations such as a carotid obtained from medical images and an aneurism. The actual algorithm is robust but nevertheless there is a limitation in the size of the problems that we can solve. This is due to the fact that at each step the non-linear shell problem is solved by a direct method. This is mandatory due to the condition number. In order to overcome this restriction it is necessary to develop different solution methods.

[4] team REO

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

Keywords: *active mechanics*, *biomechanics*, *data assimilation*.

Participants: Frédéric Bourquin, Dominique Chapelle, Philippe Moireau, Jacques Sainte-Marie, Michel Sorine [team SOSSO2].

We have made some significant progress towards performing data assimilation in order to use measurements in conjunction with model simulations to obtain some estimations of the state and parameters of the system, which was one of the major (long-term) objectives of the ICEMA and ICEMA2 projects for diagnosis purposes.

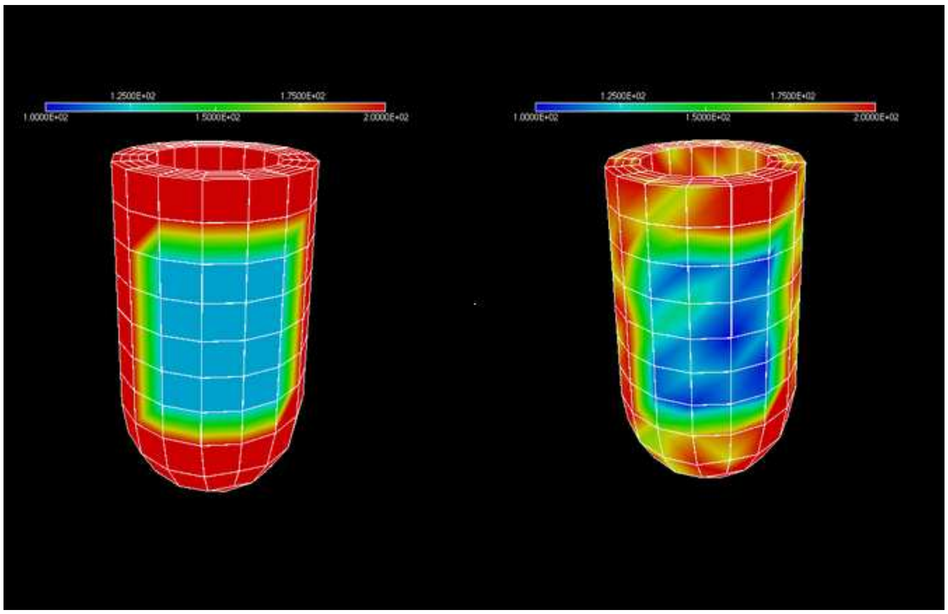

Figure 1. Data assimilation: original values on the left, assimilated values on the right

At the present stage we have achieved a preliminary validation of this data assimilation approach using synthetic data (see Figure 1), and intensive efforts are currently under way to use actual clinical measurements, which of course represents an important applicative challenge [10]. This was the topic of a research work carried out in the framework of CEMRACS 2004 by P. Moireau in collaboration with M. Sermesant and R. Andriantsimiavona (King's College London), with the participation of D. Chapelle, P. Le Tallec and J. Sainte-Marie. This work was then further pursued during a 6 weeks stay of P. Moireau at KCL, as part of his DEA internship performed in MACS and with the perspective of a PhD continuation.

7. Contracts and Grants with Industry

7.1. Michelin: simulation of the behavior of reinforcing sheets in tyres

Participants: Dominique Chapelle, Marina Vidrascu.

The reinforcing sheets in tyres are thin, strongly anisotropic layers made of a stiff material embedded in the tyre rubber in order to increase the structural rigidity, see Figure 2. Classical shell models and finite elements

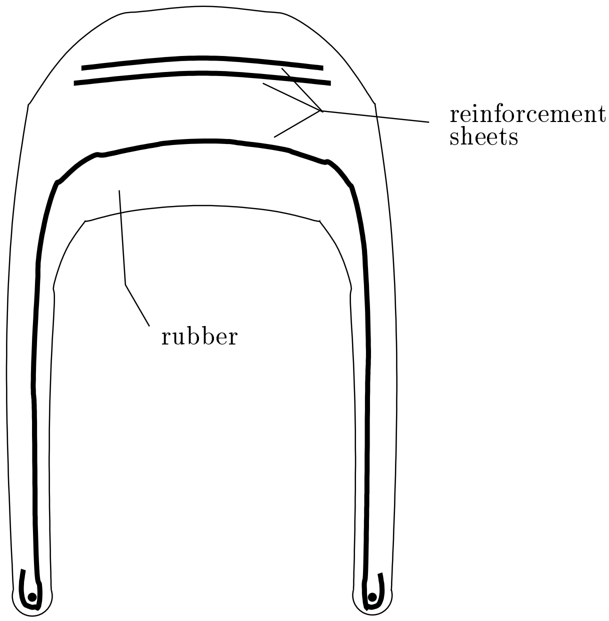

Figure 2. Cross-section of a tyre

are not well-suited to such cases, hence the purpose of the partnership is to develop efficient numerical methods to simulate the behavior of reinforcing sheets in an industrial software environment.

The objective of this year's work was to formulate and develop the axisymmetric shell elements corresponding to the previously developped 3D-shell elements, with the motivation that many finite element analyses in the tyre R.&D. are performed in axisymmetric conditions.

8. Other Grants and Activities

8.1. National projects

8.1.1. ACI CONSTRUCTIF (COuplage de coNcepts pour la Surveillance de sTRUCTures mécaniques InFormatisées - Coupling of concepts for the surveillance of computerised mechanical structures)

Participants: Frédéric Bourquin, Dominique Chapelle.

This project[5] coordinated by the SISTHEM team (IRISA) is part of the "ACI Sécurité Informatique"[6] and was launched in September 2003 (for 3 years). The objectives are:

- the coupling of statistical models of sensor data with models of the physical phenomena governing the instrumented structures for monitoring purposes;
- the investigation of the combined use of multidisciplinary approaches – namely, statistical inference, data assimilation, finite element model updating and optimization methods – with a view to diagnosing and localising damage.

[5] http://www.irisa.fr/sisthem/index-fr.htm
[6] http://acisi.loria.fr/

8.2. International projects

8.2.1. RTN Project "SMART"

Participants: Michel Bernadou, John Cagnol, Dominique Chapelle, Marina Vidrascu.

This project[7] – an RTN project of the fifth European Framework Program – started in November 2002 (for 4 years). The aim is to foster research and to provide training for researchers in the field of new materials and adaptive systems. "New materials" is used here as a generic term for "functional" materials whose physical or chemical properties are used in the design of control elements yielding smart systems. The scientific objectives of the research are to develop efficient mathematical methods and numerical tools for modelling, control and numerical simulation.

This network project is coordinated by ESIEE[8], MACS being the other French member out of a total of 11 members from 8 European countries.

8.2.2. NSF-INRIA Project "Control of interactive structures with dynamic shells"

Participants: Michel Bernadou, John Cagnol, Dominique Chapelle.

This project supports collaborative research between our group and the University of Virginia (principal investigator Irena Lasiecka), on problems related to stabilization and optimal control of dynamical shell models where control actions and sensing are implemented via smart materials technology.

8.2.3. Other long-term collaborations

- Collaboration on numerical locking with MIT and ADINA R&D (Klaus-Jürgen Bathe).

9. Dissemination

9.1. Various academic responsibilities

Dominique Chapelle:

- Vice-chairman of INRIA-Rocquencourt Project Committee;
- Scientific organizer of NumD evaluation seminar (13-14 October);
- Member of the editorial board of "Computers & Structures";
- Elected member of the board of SMAI;
- Elected treasurer of GAMNI ("Groupement pour l'Avancement des Méthodes Numériques de l'Ingénieur");
- Scientific coordinator of the CEA-EDF-INRIA schools organized by INRIA.

9.2. Teaching activities

- Jacques Sainte-Marie :
  - Courses on linear algebra and formal calculus, University of Versailles-Saint Quentin, spring 2004.
- Marina Vidrascu : Course *Mathematical fundamentals of the finite element method*, at école Supérieure d'Ingénierie Léonard de Vinci.

[7] http://www.esiee.fr/smart-systems/index.php
[8] http://www.esiee.fr/

9.3. Participation in conferences, workshops and seminars

Dominique Chapelle

- Organizer of CEA-EDF-INRIA School "Electromechanical behaviour of the heart: confronting models with data towards medical applications" (April 26-30, 2004);
- Speaker at ECCOMAS 2004, July 24-28, Jyvaskyla, Finland;
- Speaker at Scilab Conference 2004 (December 2-3), Rocquencourt;
- Invited seminar at Paris 6 (March 12th).

Philippe Moireau

- Student intern at CEMRACS04 “Mathematics and Applications in Biology and Medicine”, CIRM Marseille, July 2004.

Jacques Sainte-Marie

- Course “Modelling and estimation of the cardiac electromechanical activity”, Ecole CEA-EDF-INRIA “Electromechanical behaviour of the heart: confronting models with data towards medical applications”, INRIA - Rocquencourt, April 2004;
- Course “Modelling and simulation of the electromechanical coupling in the heart”, CEMRACS04 “Mathematics and Applications in Biology and Medicine”, CIRM Marseille, July 2004.

Marina Vidrascu

- Speaker at ECCOMAS 2004, July 24-28, Jyvaskyla, Finland;
- Invited seminars at University Tunis (June 23rd), CEMRACS04 (August 17th);
- Haemodel workshop 2004 in Graz, April 13-14.

10. Bibliography

Major publications by the team in recent years

[1] D. CHAPELLE, K. J. BATHE. *The Finite Element Analysis of Shells – Fundamentals*, Springer-Verlag, 2003.

Articles in referred journals and book chapters

[2] D. CHAPELLE, A. FERENT, K. BATHE. *3D-shell elements and their underlying mathematical model*, in "Math. Models Methods Appl. Sci.", vol. 14, 2004, p. 105–142.

[3] J.-F. GERBEAU, M. VIDRASCU, P. FREY. *Fluid-Structure Interaction in Blood Flows on Geometries coming from Medical Imaging*, INRIA RR-5052 (2003) to appear in Comp. & Struct..

[4] J. SAINTE-MARIE, S. MAMMAR, L. NOUVELIÈRE, V. ROUAULT. *Sub-optimal longitudinal control of road vehicles with capacity and safety considerations*, in "ASME Journal of Dynamic Systems, Measurement and Control", vol. 126, 2004, p. 26-35.

[5] J. SAINTE-MARIE. *A sampling technique for band-limited signals with respect to a transform associated with a group representation*, in "Sampling Theory in Signal and Imaging Processing", In press, 2004.

Publications in Conferences and Workshops

[6] E. BALMÈS, D. CHAPELLE, C. DELFORGE, A. HASSIM, J. LECLÈRE, M. VIDRASCU. *OpenFEM: an opensource finite element toolbox*, in "Proceedings of the ECCOMAS Conference", 2004.

[7] D. CHAPELLE, J. SAINTE-MARIE. *Modeling and estimation of the cardiac electromechanical activity*, in "Proceedings of the ECCOMAS Conference", 2004.

Miscellaneous

[8] D. CHAPELLE, C. MARDARE, A. MÜNCH. *Asymptotic considerations shedding light on incompressible shell models*, Submitted to J. of Elasticity, 2004.

[9] P. LE TALLEC, P. HAURET, J. GERBEAU, M. VIDRASCU. *Fluid Structures Interaction Problems in Large Deformations.*, submitted.

[10] M. SERMESANT, P. MOIREAU, O. CAMARA, J. SAINTE-MARIE, R. ANDRIANTSIMIAVONA, R. CIMRMAN, D. HILL, D. CHAPELLE, R. RAZAVI. *Cardiac function estimation from MRI using a heart model and data assimilation : advances and difficulties*, Submitted to FIMH2005 conference.