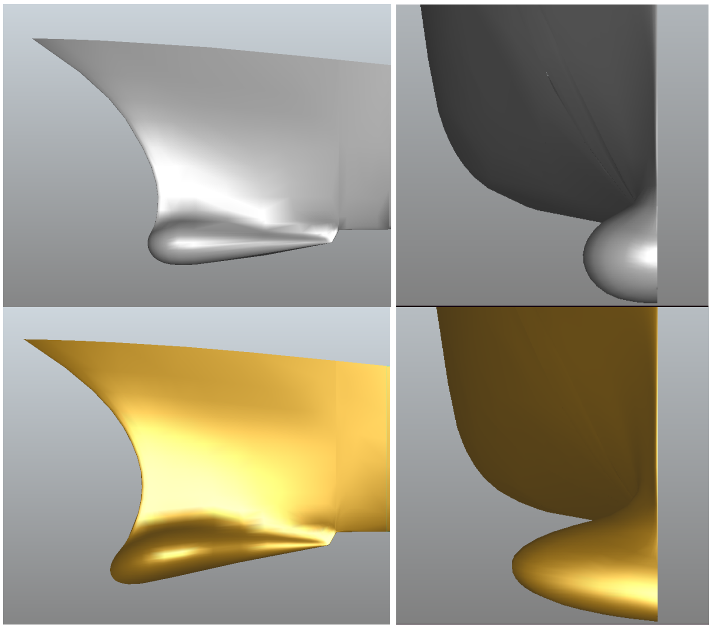
Reduced Order Methods in Computational Fluid Dynamics: state of the art and perspectives in COST EU-MORNET

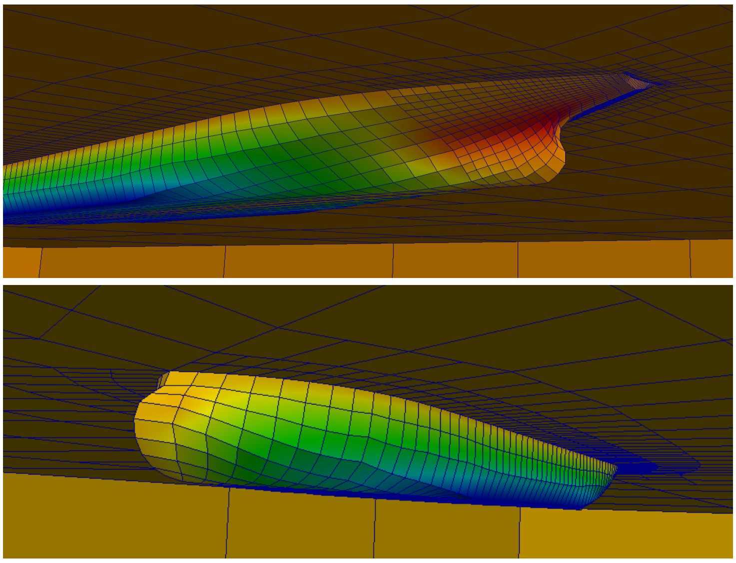
The mini-workshop deals with **reduced order methods in computational fluid-dynamics** and related aspects: domain decomposition, coupled physics, interfaces, optimization, control, inverse problems, industrial applications, benchmark test cases, parametrizations, sensitivity analysis, ...

The mini-workshop is organized with the aim of creating open and informal discussions and exchange of ideas, visions and experiences.

Dates: Monday, **22 February**, **14:30 – 18:15**,
Tuesday, **23 February**, **9:30 – 16:00**

Place: SISSA Lecture Room A-005, ground floor, via Bonomea 265, Trieste





Round Tables and discussions on software developments and industrial research, with current challenges and needs, led by SISSA mathLab young researchers:

- Dr. Andrea Mola
- Dott. Giovanni Corsi
- Dott. Marco Tezzele
- Dott. Filippo Salmoiraghi

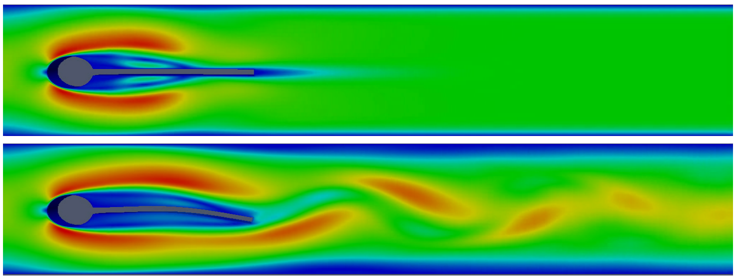
Opening:

- Prof. Gianluigi Rozza, SISSA
- Prof. Wil Schilders, TU Eindhoven

Speakers:

- Dr. Francesco Ballarin, SISSA
- Dr. Valentina Dolci, PoliTo
- Dr. Silke Glas, Ulm
- Dr. Stefano Lorenzi, PoliMi
- Dr. Eleonora Musharbash, EPFL
- Dr. Federico Negri, EPFL
- Dr. Matteo Ripepi, DLR

No Fees.
Registration by email: morepas2015@sissa.it



Related Links

- SISSA mathLab website: mathlab.sissa.it
- COST action website: cost.eu/COST_Actions/tdp/TD1307
- EU-MORNET website: www.eu-mor.net

February 22, 2016, Lecture Room 005, ground floor

2:30 pm: Welcome, **Prof. Gianluigi Rozza**, SISSA, Trieste, Italy and WG1 coordinator

2:45 pm: COST EU-MORNET initiatives and network, workgroups, **Prof. Wil Schilders**, TU Eindhoven, Netherlands and COST EU-MORNET Chairman

3:15 pm: Reduced basis methods for variational inequalities - **Silke Glas**

This talk will consist of two parts: A survey of reduced basis methods (RBM) for parabolic variational inequalities in a space-time formulation and new insights for a RBM of elliptic variational inequalities formulated as quadratic problem. In the first part, we consider variational inequalities with different trial and test spaces and a possibly noncoercive bilinear form. Well-posedness has been shown under general conditions that are e.g. valid for the space-time formulation of parabolic variational inequalities. Using space-time formulations, we do not have a time-stepping scheme anymore, but take the time as an additional variable in the variational formulation of the problem. Combining the RBM with the space-time formulation, a residual based error estimator has been derived. In the second part of the talk, we will present a new approach to elliptic variational inequalities. Transforming the elliptic variational inequality into a quadratic problem, we are able to apply the Brezzi-Rappaz-Raviart theory and to derive error estimators, which are decomposable and efficiently computable. In this talk, we will present numerical results of computational models for both approaches.

4:00 pm: Model order reduction strategies for blood flow and mass transport problems in hemodynamics - **Federico Negri**

In the cardiovascular context, mass transfer refers to the exchange of substances (e.g. oxygen) between blood and the arterial wall. The solute distribution and availability inside the vessels and into the vascular walls is strongly related to flow dynamics of blood. In particular, it has been observed that irregular flow patterns result in disturbed mass distributions, which may eventually lead to the development of atherosclerotic diseases. The numerical simulation of solutes dynamics could therefore be useful for revealing the relationships between irregular flow patterns, mass transfer, and possible pathogenesis. However, the predicted solute distribution is significantly affected by a number of unknown, uncertain or patient-specific parameters which enter the underlying mathematical models. In turn, these parameters may need to be either estimated, calibrated or optimized. Therefore, reduced-order models could bring great advantages by enabling a more extensive parameter exploration and fast simulations. To this end, in this talk we present suitable reduction strategies which combine the matrix discrete empirical interpolation method and a POD-based reduced basis method.

4:45 pm: Coffee Break (Lobby, ground floor)

5:15 pm: Dynamical Low rank approximation of incompressible Navier-Stokes equations with random parameters - **Eleonora Musharbash**

We investigate the Dynamically Orthogonal approximation of time dependent incompressible Navier Stokes equations with random parameters. The approximate solution is sought in the low dimensional manifold of functions with xed rank, written in separable form, and it is obtained by performing a Galerkin projection of the governing equations onto the time-dependent tangent space of the approximation manifold along the solution trajectory. Numerical tests at moderate Reynold number will be presented, with emphasis on the case of stochastic boundary conditions.

6:00 pm: Questions and discussions

8:30 pm: Pizzata, Trieste City Center (paid by participants)

February 23, 2016, Lecture Room 005, ground floor

9:30 am: Parametrized Proper Orthogonal Decomposition with a reduced snapshot set for aeronautical applications - **Valentina Dolci**

The increasing complexity of engineering systems has caused an increased computational burden to simulate how a specific product will perform. The run length that a full model simulation can require will make the application of any optimization algorithm very time consuming. A way to solve this problem is the surrogate model approach. The basic of this philosophy is the construction of a simplified mathematical representation of the computationally expensive complete description of the problem (i.e. for aerodynamic problems the Navier-Stokes equations) starting from a reduced number of initial CFD solutions. The surrogate model can then be used for the numerous function evaluations required by an optimization algorithm, a design space exploration or a sensitivity analysis. The intrinsic optimality and the simplicity of implementation make the proper orthogonal decomposition the ideal candidate to build a surrogate model. POD can be applied to non-linear problems but it remains a linear procedure. Using the snapshot method, the initial number of freedom degrees can be easily reduced from some millions to the total snapshots number that in this work is under 30. To implement POD with the snapshot method the only difficulty is the solution of an eigenvalue problem with a dimension equal to the snapshot number. Without the need of a projection of the full-model problem in a reduced basis, the high-energy components of a field are extracted. The optimality of the POD is in the energetic sense in fact this method is able to generate a vector basis maximizing the projections of all the initial fields (snapshots) among the vector directions. Applications of this approach are presented for a transonic airfoil with geometry changes and for a full airplane in the bi-parametric space composed by the angle of attack and the sideslip angle. The second application pays attention to the position choice of the initial snapshot set. Exploiting the properties of statistical inference, different studies are performed comparing various initial snapshot set obtained with full factorial planes and quad-tree methodology.

10:15 am: CFD based ROMs for Aeronautical Applications - **Matteo Ripepi**

The advent and development of large-scale high-fidelity computational fluid dynamics (CFD) in aircraft design is requiring, more and more, procedures and techniques aimed at reducing its computational cost in order to afford accurate but fast simulations of, e.g., the aerodynamic loads. The adoption of reduced order modeling techniques in CFD represents a promising approach to achieve this goal. Several methods have been developed to obtain reduced order models (ROMs) for the prediction of steady and unsteady aerodynamic flows using low-dimensional linear subspaces as well as nonlinear manifolds, whose performances may be further improved by applying hyper-reduction procedures. In this talk, it is presented the activity done at the German Aerospace Center (DLR) in the context of model order reduction and surrogate modeling for multidisciplinary applications, design and optimization. Different examples are shown to demonstrate the use of the ROMs in aeronautical applications, as for fusing experimental and CFD data, accelerating CFD computations, obtaining a fast loads prediction across the flight envelope, or accelerating multidisciplinary optimizations. The ROMs approches are demonstrated for airfoils, wings and aircraft in subsonic and transonic flows.

11:00 am: Coffee Break (Lobby, ground floor)

11:30 am: POD-Galerkin method for Finite Volume approximation of Navier-Stokes and turbulent RANS equations - **Stefano Lorenzi**

Model order reduction can be employed whenever fast simulations are required in engineering. A typical application of this approach is the control context. Reduced order model can be employed for instance as the basis for the synthesis and the verification of controllers in the framework of the realization and validation of the control system. Even if in principle the several ROM techniques can be applied to different approximation schemes (i.e., finite difference, Finite Volume (FV), Finite Elements (FE), spectral methods), the most widespread method used is the FE method. The interest to study the FV approximation relies on the fact that, from an engineering point of view, the latter is considered robust, computationally inexpensive, and suitable when the conservativity of the numerical flux is a relevant issue, as in the fluid-dynamics application. Even if the FE can be more accurate, the FV is usually chosen for industrial applications since it is easily applicable to realistic and physical context, it does not require any particular functional framework as FE and it preserves locally the conservation laws. Another remarkable issue is that the fluid flow usually considered in the engineering field is turbulent. The eddies created by the turbulence span a large range of length and time scales. Accordingly, they can be modelled with several degree of accuracy according to the resolution needed for the engineering application. Even if Large Eddy Simulation and Direct Numerical Simulation are very accurate (but computational expensive), for most engineering applications the Reynolds-Averaged Navier Stokes (RANS) equations with suitable turbulence models are sufficient to describe the main time-averaged properties of the flow (velocity, pressures, and stresses). In this work, the efforts have been put to develop a ROM for Computational Fluid Dynamics (CFD) application based on FV approximation, starting from the results available in turbulent RANS simulations in order to enlarge the application field of POD-ROM technique to more industrial fields. The approach is tested in the classic benchmark of the numerical simulation of the 2D lid-driven cavity. In particular, two simulations at Re=1.000 and Re=100.000 have been considered in order to assess both a laminar and turbulent case. Finally, a parametrized application related to a nuclear engineering problem is also presented.

12:15 pm: Reduced order models for parametrized problems in computational fluid dynamics: biomedical applications - **Francesco Ballarin**

In this talk we discuss a computational reduction framework for parametrized time dependent viscous flows, based on a offline/online splitting between an high fidelity model (offline) and a reduced order one (online). Special attention will be devoted to the stabilization of the resulting online system, shape parametrization maps to efficiently handle deformation of the computational domain as well as domain decomposition and interface management. We will show some applications of the proposed framework to optimal control problems, fluid-structure interaction as example of multiphysics application. A special attention is devoted on cardiovascular flows as example of application of reduced order methods in biomedical field.

1:00 pm: Lunch (Lobby, ground floor)

2:30 pm: Challenges for Reduced Order Methods in Industrial Applications: Opportunities in Aero/Naval/Mechanical Engineering - **G. Corsi, A. Mola, F. Salmoiraghi, M. Tezzele, G. Rozza**

We present in the framework of some industrial projects in aero/naval/mechanical engineering fields some current challenges for reduced order methods to provide computational savings, real-time computing, efficient shape parametrization for design and optimization, as well as exhaustive exploration of the parameters space. The state-of-the-art problems we present are examples of current challenges in computational science and engineering in need of new contributions from the ROM community to address several current issues. Among them, we mention a proper parametrization (number of parameters, ranges of variation, sensitivity), an efficient and automatic management of shapes from CAD to simulation (and optimization/deformation/adaptivity), as well as dimension reduction in parameters studies. Examples are shown from complex studies in CFD and multiphysics, as well.

This focus talk, followed by a round table, wants to create a bridge within COST EU-MORNET between WG1 methodological topics and WG2 and WG3 more focused on applications, industrial proof-of-concept based on ROM and benchmarks.

3:15 pm: Round Table on ROM software developments

3:45 pm: Final remarks, **Prof. Gianluigi Rozza, Prof. Wil Schilders**