Preface to the first volume of *Model Order Reduction*

This is the first of the three-volume set *Model Order Reduction* intended to be used as a handbook in partial fulfilment of the goals of the COST Action EU-MORNET. The first two volumes deal with methods and algorithms, while the third and final volume is devoted to specific applications. Before discussing the contents of Volume 1 (for the contents of Volumes 2 and 3, see the respective editorials there), we would like to explain the background of this project.

EU-MORNET: Model Order Reduction in Europe

European researchers have realized the importance of Model Order Reduction (MOR) and reduced-order modeling already since the 1990s, in the scientific computing and computational engineering communities as well as in the area of systems and control. Since then, the interest has grown steadily, with many workshops and conferences having been organized, and several MOR research groups emerging. In the early 2000s, the first workshops were organized that brought researchers from these various areas together. This includes the 2003 workshop on "Dimension Reduction of Large-Scale Systems" at the Mathematical Research Center Oberwolfach and the 2005 workshop "Model Order Reduction – Coupled Problems and Optimization" at the Lorentz Center in Leiden. Both inspired the publication of tutorial-style collections, leading to two of the first books on MOR.[1,2] At the same time, the first research monograph fully dedicated to MOR appeared.[3] In addition, comprehensive European projects like CODESTAR ("Compact modelling of on-chip passive structures at high frequencies", 2002–2004), CHAMELEON-RF ("Comprehensive High-Accuracy Modelling of Electromagnetic Effects in Complete Nanoscale RF Blocks", 2004–2006), and O-MOORE-NICE! ("Operational MOdel Order REduction for Nanoscale IC Electronics", 2007–2010) made abundant use of MOR. The European Research Training Network COMSON ("Coupled Multiscale Simulation and Optimization in Nanoelectronics", 2007–2009) also had a major task on MOR, and organized an autumn school on the Dutch island of Terschelling. It is still remembered by many participants, due to the nice food and luxurious accommodation, but also because many leading MOR researchers from all over the world were present. During this autumn school, there

1 Peter Benner, Volker Mehrmann, and Danny C. Sorensen (Eds.), *Dimension Reduction of Large-Scale Systems*, Lecture Notes in Computational Science and Engineering, Vol. 45, Springer-Verlag, Berlin/Heidelberg, 2005.

2 Wilhelmus H. Schilders, Henk van der Vorst, and Joost Rommes (Eds.), *Model Order Reduction: Theory, Research Aspects and Applications*, Mathematics in Industry, Vol. 13, Springer-Verlag, Berlin/Heidelberg, 2008.

3 Athanasios C. Antoulas, *Approximation of Large-Scale Dynamical Systems*, SIAM, Philadelphia, 2005.

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was a first discussion on starting a European network on MOR, but due to the lack of funding opportunities, there was no immediate follow-up.

In 2013, Peter Benner, chair of one of the MOR centers in Europe (the Max Planck Institute for Dynamics of Complex Technical Systems in Magdeburg), together with Albert Cohen (Paris), Mario Ohlberger (Münster), and Karen Willcox (then at MIT) organized a workshop in the Luminy mathematics research centre CiRM, located beautifully off the coast in the south of France, and this turned out to be the ideal setting for the preparation of a so-called COST Action on MOR. The lectures during the day and the very pleasant atmosphere in the evenings put us in the right mood for writing. The aim of the proposal was to "bring together all major groups in Europe working on a range of model reduction strategies with applications in many of the COST domains". The proposal survived the first round, and was admitted to the second round, which meant going to Brussels for an interview with a very broad and general committee. The overall chances of success were approximately 4 %, but we succeeded and hence EU-MORNET was born. The first management committee meeting took place in Brussels in April 2014, and since then many activities have been organized and undertaken. Highlights were the MoRePaS conferences in Trieste and Nantes, the Durham workshop in August 2017, organized jointly with the London Mathematical Society, and MODRED held 2017 in Odense. The network was growing constantly, and when the funded period of EU-MORNET ended in April 2018, more than 300 researchers had joined the network. We hope to sustain this network, e. g., via its webpage eumor.net, as coordination of activities has turned out to be very fruitful, it has put MOR in the spotlights, and we observe that the interest in MOR is only growing: many European projects make use of it, or emphasize its importance like the recently ended ECSEL project Delphi4LED. A glimpse at some of the various applications encompassing MOR in its computational workflows is provided in Volume 3 of this handbook project. We are very grateful to the COST Organization for supporting this initiative, thereby bringing MOR in Europe to the next level. This handbook also serves as the ultimate dissemination effort of EU-MORNET and will hopefully help generations of new researchers and practitioners to get a gentle introduction into the field and to find inspiration for their own development and research work.

Introduction to Volume 1

This first volume starts with an introductory chapter to MOR in general as a very broad field of research, encompassing multiple techniques with applications in a wide variety of fields. This chapter serves two main purposes. On the one hand, it provides an introduction to the handbook project itself, helping the reader navigate through the three volumes, explaining their organization, providing pointers into the various chapters where specific methods are presented or where particular applications are further explored. Additionally, this first chapter also serves as a conduit to introduce

concepts and notation used throughout the various chapters and volumes, in an attempt to support, simplify and enrich the reader's experience when probing the information provided in the three volumes of "Model Order Reduction".

After this initial, introductory chapter, all chapters of this first volume mostly focus on the concept of MOR applied in a system-theoretical context. The common principle among methods and algorithms in this setting is the basic assumption that there is an underlying system description whose behavior can be determined from the knowledge of the dynamics of a set of state variables. Specific developments both in theory and applications, including deployment in commercial CAD tools, took place over the years in specific settings and disciplines, sometimes using different language and notation. However, all such methods share a common framework, which we attempted to capture in this book.

The second chapter in this volume, by T. Breiten and T. Stykel, is devoted to methods associated with the concept of energy of a system and with the problem of how to represent it in balanced coordinates. This enables discarding the least relevant states from an input-output perspective. The resulting truncated system has several very interesting properties, which are discussed in the context of linear and nonlinear reduction.

The third chapter by L. Feng and P. Benner delves into the realm of moment-matching methods (also known as Padé-type approximations, relating to rational interpolation) as a metric for reduction, and details methods based on projection techniques for compressing linear, nonlinear and parametric systems.

The next chapter of P. Tiso et al. is devoted to modal truncation applied to linear and nonlinear systems. This chapter discusses techniques based on analysis of the system dynamics, in particular the observation of its eigenmodes and consequent truncation leading to reduced-order models.

Enforcing specific desirable or required system properties after reduction is the target of the next chapter, by S. Grivet-Talocia and L. M. Silveira, which is devoted to post-processing techniques. In particular, the most prominent techniques for enforcing passivity of linear systems via perturbation approaches are introduced and discussed.

The following chapter serves as an interesting bridge between moment-matching methods described as rational interpolation, to data-driven interpolation techniques connecting to approaches that start from measurements of the system. This chapter, by D. Karachalios, I. V. Gosea and A. C. Antoulas, introduces the Loewner framework for system reduction and connects to moment matching, interpolation and projection.

The seventh chapter, by R. Zimmermann, continues the trend of discussing interpolation methods, but it introduces manifold interpolation as a supporting tool in the reduction framework of parameterized systems.

The final three chapters are entirely dedicated to exploring model reduction techniques fueled by data obtained from system behavior.

The eighth chapter, by P. Triverio, discusses Vector Fitting, a data-driven algorithm where samples or measurements of the system response are used to construct a reduced representation.

The ninth chapter, by G. Santin and B. Haasdonk, stays in the realm of data-driven reduction and introduces kernel methods as surrogate system models. It introduces a series of methods where the system representation is unknown or eschewed and a reduced representation is constructed or estimated from the information garnered by sampling the system or its outputs.

Last but not the least, the tenth and final chapter, by J. Kleijnen, presents Kriging techniques: a set of data-driven interpolation techniques for generating a reduced model through kernel regression assuming an underlying Gaussian distribution.

At this point, we would like to thank also all the contributing authors who brought this project to life, the numerous anonymous reviewers who ensured the quality of the 30 chapters of the three volumes of the Model Order Reduction handbook series, and last but not least Harshit Bansal, who helped with producing the index for every of the three volumes. Our gratitude also goes to the De Gruyter staff, and in particular to Nadja Schedensack, for accompanying this project constructively over more than four years, with unprecedented patience.

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