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Vladimir Buljak

Inverse Analyses with Model Reduction

Proper Orthogonal Decomposition in Structural Mechanics

Springer

Vladimir Buljak
Politecnico di Milano
Dipartimento di Ingegneria
Strutturale
Piazza Leonardo da Vinci 32
20133 Milano
Italy
buljak@stru.polimi.it

ISSN 1860-482X e-ISSN 1860-4838
ISBN 978-3-642-22702-8 e-ISBN 978-3-642-22703-5
DOI 10.1007/978-3-642-22703-5
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2011941196

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

The methodology of inverse analysis, the origins of which may be regarded as remote and deeply rooted in the history of structural mechanics, has in relatively recent times, emerged as a modern and fast growing area of engineering sciences. In several technological fields, evident are importance and usefulness of reliable transition from experimental data on systems, structures "in primus", to quantitative assessments of crucial properties and possible damages in those systems. Such a kind of assessment means accurate estimations of parameters hidden in mathematical models at present available to simulate and predict the system behavior in service.

The achievement of such ambitious task clearly requires a synergistic convergence of diverse scientific fields: mathematics, usually with their traditional concepts and solution methods (e.g., ill-posedness of problems; minimization/maximization of nonconvex functions), experimental developments in terms of suitable devices, computational techniques and relevant tools.

The growth of computers according to "Moore's law" in the last four-five decades has been, and still is, essential also for the expansion of the inverse analysis developments and applications. Such a link was evidenced in 1986 by Richard Feynman through his celebrated warning on computers ("garbage in, garbage out") after the disaster of the Challenger.

The role of mathematics (specifically, mathematical programming and soft-computing methods, stochastic approaches including Kalman filters, et alia) in inverse analyses is widely important and turns out to be consistent with authoritative recommendations in the engineering history (e.g.: Leonardo da Vinci: "no human investigation is true science if not based on mathematical demonstrations"; Eduardo Torroja: "in the art of building without a mathematical background the designer has no success").

Experiments and measurements, suitably selected by sensitivity assessments, clearly represent the basis of inverse analyses, in full agreement with memorable warnings by great engineers (let us remember Leonardo da Vinci again: "our evaluations may fail, experiments do not"; and Eugène Freyssinet: "when

experiment and computation disagree, always computation is wrong"; and also Dan Drucker: "design to design structures is still in large measure based on experience and tests").

The present trends towards synergy of experiments, mathematics and computations, turn out to concern more and more frequently research, engineering practice and scientific education. Popular is becoming at present the following statement by John von Neumann: "science mainly makes models; the justification of such construct is solely that it is expected to work".

This author provides a remarkable contribution to inverse analysis applications in the field of structural mechanics and engineering problems. Peculiar features of this book are the attention paid to the computer implementation of timely procedures for parameter identification and the availability in various chapters of several routines related to popular software like MATLAB and to a widely employed commercial finite element code.

Readers are likely to appreciate detailed treatment of selected inverse problems in structural mechanics and accurate description and employment of representative innovative procedures, practically useful in terms of operative economy (particularly "proper orthogonal decomposition" and "radial basis functions" interpolation). It is desirable that, in future editions of this book, treatments of inverse problems by the same criteria be devoted also to supplementary meaningful subjects and related issues, such as stochastic approaches and relevant computational procedures: these issues are worth of further research efforts and broader applications.

To the study of inverse analysis methodology and to its applications in real life problems, this young author has successfully dedicated his doctoral thesis and his first two years of "post-doc" research and teaching activities in a university environment.

This Foreword ends with cordial, warm wishes to the author for success in his scientific research and teaching career and in future amplifications of this book, dedicated to the growing attractive and productive area of inverse analysis in engineering and technologies.

Giulio Maier

Preface

The goal of this book is to present a modern approach to inverse analyses (IA) that combines traditional framework with numerical techniques used for model reduction. In the main focus are parameter characterization problems in structural mechanics, although most of the material is applicable with slight modifications also to other scientific and engineering fields. The book is intended for engineers and scientist who would like to learn, up to the very details, how to bring together all the necessary pieces into working programs that will solve given inverse problem.

Since the main emphasis was on the implementation, selected algorithms are described into the details required for their implementation, and for all of them practical codes within MATLAB programming language are given with full listings. The codes are written in general way, so it shouldn't be difficult to translate them into any other programming language.

An inverse analyses procedure puts together experimental mechanics, numerical modeling and mathematical programming. For a successful IA procedure one needs to tackle all of these problems. In the structural context discussed in this book, with a traditional approach, simulations of the experiments are done by finite element modeling (FEM), and most frequently commercial codes are used for this purpose. In the problems, tackled within the book, that used this approach to IA a commercial code ABAQUS was selected, while the routines that are written to automatically modify FE models and run the simulations are presented and discussed.

As far as mathematical programming is concerned, given the objective of the book, the most popular optimization algorithms are selected and described up to the details of their successful implementation, while detailed theoretical background descriptions were omitted. Nevertheless, an attempt was made to guide interested readers for useful further readings on the given topics. Optimization algorithms are treated in Chap. 2, and the material in this chapter should serve for the reader to become familiar with all the main concepts of iterative optimization algorithms. The author strongly believes that, after reading this chapter, a careful reader will be

able to write his own program that solves numerically an optimization problem by using any of the algorithms discussed in the chapter.

Model reduction technique presented in this book is based on Proper Orthogonal Decomposition (POD) and Radial Basis Functions (RBF). In Chap. 3 it is explained up to very details how these two mathematical techniques are combined into a powerful computing tool that can have an accurate computation of system responses in a computing times shorter by few orders of magnitude with respect to traditional numerical modeling techniques used in structural context (e.g. FE modeling). The construction of proper orthogonal basis in the discreet theory approach was discussed in details, and three different derivations are presented and illustrated with simple examples. The objective of this chapter was to connect the ideas behind the POD theory to the present context and to show how the basic principles developed in different fields can be successfully used also in structural mechanics, and by author's opinion in many other computational problems.

The other mathematical tool used in this reduced basis model, namely RBF interpolation is also described in detailed manner and covered by numerical examples that should serve for a better understanding. Finally, in the last part of Chap. 3, it was demonstrated how the two techniques can be combined into a reduced model used for the computation of system responses in structural mechanics context. This chapter is written with the intentions to explain all the concepts on which reduced basis model here presented is built. The author's opinion is that the careful reader should be capable to, by applying the analogy, employ the described model also to other physical phenomena.

In the last two chapters it was demonstrated how all the previous pieces are put together into a fully working inverse analysis procedure. Chap. 4 showed all the necessary steps for building a so-called traditional IA procedure, where FE simulations are used for the prediction of the system responses. Even though the book presented a modern approach to the inverse analyses, where a reduced basis models should be used for the prediction of system responses, by author's opinion also the traditional approach is very important as it anyhow should be used in some stages of the development. Since the main accent of the book was on the implementation, also in this chapter a detailed description of all the necessary programs was discussed and the developed codes are given in full listings. The material presented in this chapter should be enough for the reader to become familiar with all the elements of practical IA procedure. In the chapter two different case studies are considered that should be used as guidelines for any other similar problem. From this chapter readers should learn how to write from the very beginning a fully working inverse analyses procedure in the structural context by coupling MATLAB routines with commercial FEM code ABAQUS.

Finally, in Chap. 5 of the book it was shown how to incorporate the developed reduced basis model into an inverse analysis procedure. With a fast computational tool like the one developed in Chap. 3, inverse analysis becomes fast and robust. This feature was demonstrated in the examples treated in this chapter. It is shown how to build standalone software which, once that it is calibrated for a given experiment, can be further routinely used on a fast and effective way.

Author believes that the selected material presented in this book should be enough to introduce the readers to the problems encountered in the inverse analysis field. The examples treated in the book should help for a better understanding of all the presented concepts. Author hopes that the book will serve also as inspiration for many different applications of this fast growing scientific field.

Vladimir Buljak

Acknowledgments

I would like to take this opportunity to thank Professor Giulio Maier from Structural Department at Politecnico di Milano, for passing an interest of inverse analyses to me during my Ph.D. work and later, during my "post-doc" phase. His charisma, inexhaustible spirit, dedication to the research, enthusiasm, wide knowledge and above all, friendship have been a great help and inspiration for me.

Special thanks go to Professor Ryszard Białecki from Silesian University of Technology, Gliwice, for his time spent with me during long discussions about Proper Orthogonal Decomposition, on a number of occasions on different conferences. I feel deeply honored for having opportunity to meet and discuss with such a great scientist like Professor Białecki.

I owe my gratitude to Dr. Ziemowit Ostrowski, who I had a fortune to meet. His excellent work was a valuable resource of information for me.

I believe that a significant contribution to this book cames from my colleagues and friends: Dr. Fabrizio Cacchione, Dr. Gabriele Della Vecchia, Dr. Riccardo Rossi, Carlo Guerini, Mohammad Reza Mahini, Dr. Tomasz Garbowski and many others. If this book is written in an understandable way, then it is a merit of these people, who were always finding time for discussions about the topics treated in this book, and who were always asking the right questions that served me as guidelines for the better presentation of the material.

Vladimir Buljak

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