

**Wiley Series in Microwave and
Optical Engineering**

Kai Chang, Series Editor

Passive Macromodeling

Theory and Applications

Stefano Grivet-Talocia
Bjørn Gustavsen

WILEY

PASSIVE MACROMODELING

Theory and Applications

STEFANO GRIVET-TALOCIA

Politecnico di Torino, Italy

BJØRN GUSTAVSEN

SINTEF Energy Research, Norway

WILEY

Copyright © 2016 by John Wiley & Sons, Inc. All rights reserved

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permissions>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Grivet-Talocia, Stefano, 1970- author.

Passive macromodeling / Stefano Grivet-Talocia, Bjørn Gustavsen.

pages cm. — (Wiley series in microwave and optical engineering)

Includes bibliographical references and index.

ISBN 978-1-118-09491-4 (hardback)

1. Electromagnetic interference—Computer simulation. 2. Analog electronic systems—Computer simulation. 3. Electric power systems—Computer simulation. 4. Passive components—Computer simulation. I. Gustavsen, Bjørn, 1965- author. II. Title.

TK7867.2.G75 2016

621.301'1—dc23

2015025341

Cover image courtesy of Gettyimages © Magnilion
Typeset in 10/12pt, Times by Spi Global, Chennai, India.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

1 2016

PASSIVE MACROMODELING

WILEY SERIES IN MICROWAVE AND OPTICAL ENGINEERING

KAI CHANG, Editor
Texas A&M University

A complete list of the titles in this series appears at the end of this volume.

此为试读, 需要完整PDF请访问: www.ertongbook.com

*To the memory of my parents S. G.-T.
To my family B. G.*

PREFACE

Numerical modeling and simulation is essential for understanding the behavior of structures and systems in practically every branch of science and engineering. Unfortunately, the enormous complexity of physical systems often prevents direct approaches where the whole system is characterized using first-principle models (typically systems of partial differential equations (PDEs)) and then simulated on a suitable computer. As an example, assessing the quality of signal and power distribution on a printed circuit board requires computing the transient electromagnetic fields over a large domain, including metal and dielectric structures with many small geometrical details, with localized nonlinear devices acting as termination networks. This task is prohibitive using a direct approach.

Divide and conquer techniques have been demonstrated as excellent alternatives to reduce this complexity and to perform efficient numerical simulations with reasonable runtimes. The overall system is first partitioned into well-defined substructures (e.g., connectors, via fields, coupled interconnect segments), which are characterized separately through approximate reduced-complexity behavioral models, so-called "macromodels." Macromodels can be identified from terminal responses either in time or frequency domain, leading to compact state-space representations of the broadband dynamics of the structure. Alternatively, macromodels may be obtained by applying model order reduction (MOR) techniques to the large systems of ordinary differential equations (ODEs) arising from a spatial discretization of Maxwell's equations in the domain of interest. Once available, these models are connected to build an approximate yet accurate representation of the whole system, which can then be solved with limited computing resources.

This approach has become a standard for the analysis of electrical interconnects at chip, package, or board level, microwave components, and high-voltage power grids including their many components such as transmission lines and transformers. The main enabling factor is linearity of the constitutive equations, which simplifies

the model extraction algorithms. The obtained macromodels can be cast as simplified electric networks made of elementary components, which can be easily simulated using off-the-shelf circuit solvers.

Although the main idea of building reduced-complexity macromodels has been pursued for several decades, an enormous advancement in algorithm and tool development took place starting from the late 1990s with the introduction of the so-called vector fitting (VF) algorithm. Despite its simplicity, this algorithm outperforms other techniques in terms of accuracy, robustness, and scalability. Thus, VF quickly became very popular and is now ubiquitous in many application areas of electrical and electronic engineering.

Additional momentum to the diffusion of macromodeling techniques came few years later with the publication of several technical papers on passivity enforcement. Only passive macromodels can be shown to preserve numerical stability in system-level transient simulations. The availability of reliable algorithms for checking and enforcing model passivity was thus the last step toward the routine application of reduced-order macromodeling. Nowadays, most electronic design automation (EDA) tools used by designers of electrical and electronic systems make extensive use of these techniques.

The rapid diffusion of passive macromodeling techniques was fostered in the early 2000s by a few software tools that were made available on the web, including the original VF code and associated software package from B.G., and the IdEM software package by S.G.-T. and his group. The importance of this subject for both academic and professional communities was further confirmed by the several dedicated tutorials, keynotes, and special sessions in many technical conferences in the fields of microwave, packaging, computer-aided design and by the fact that several leading universities worldwide started offering graduate-level courses on various aspects of macromodeling.

ABOUT THIS BOOK

The purpose of this book is to offer a complete and well-organized presentation of state-of-the-art passive macromodeling techniques, with emphasis on black-box approaches. This book can be used as a reference text for senior or graduate-level courses in electrical engineering programs, as well as a reference for both scholars and engineers active in the field of numerical modeling, simulation, design, and optimization of electrical/electronic systems.

Since the target readers may have a diverse background and experience, we included in the book some chapters with standard background material (e.g., linear time-invariant circuits and systems, basic discretization of field equations, state-space systems), as well as few appendices collecting basic facts from linear algebra (Appendix C), optimization templates (Appendix D), and signals and transforms (Appendix E). These parts may be skipped by the most experienced readers but will be valuable to more practical readers who need a self-contained book for quick reference. Furthermore, the book includes some more technical or advanced topics, which may be omitted at first reading. These topics are flagged with an asterisk (*).

In preparing this text, we have put our best effort to achieve a good compromise between readability and mathematical rigor. In fact, many excellent books and technical papers on system and control theory, identification, approximation, and reduction are

available (and duly cited in this work). Unfortunately, most of these books are hard to read for the nonspecialist. Design engineers and even graduate students in applied disciplines may fail in grasping the main concepts if the presentation flow is too formal. However, the subject of this book requires a minimum of derivation and justification of the main results in order to have a clear understanding of the advantages and disadvantages of the developed algorithms, including applicability limits. With this in mind, we tried to elaborate all main concepts and results in a mathematically precise way, but without excessive formalism. Many proofs are omitted and only sketched or left as exercises for the readers. Most crucial concepts are illustrated through dedicated examples. Each chapter is further complemented by a selected set of problems.

The first part of this book provides some basic definitions and background material on passive linear systems and circuits, setting notation for later chapters (lists of symbols and acronyms are available in Appendices A and B). Chapter 1 provides an overview of the book content and defines the context where macromodeling can or should be applied. Chapter 2 discusses linear time-invariant (LTI) systems based on their “external” or input–output characterization, without assuming any knowledge on their internal structure. Chapter 3 focuses instead on lumped LTI systems described by state-space or descriptor forms. These two chapters discuss in detail the concepts of stability, causality, and passivity – crucial properties that black-box macromodels must adhere to.

Macromodeling aims at representing complex electromagnetic systems as low-complexity equivalent circuits, or more generally, at approximating systems of PDEs via small systems of ODEs. Chapter 4 provides an overview of the necessary steps that must be undertaken to enable such approximations, based on simple 1D and 2D distributed-parameter examples. A short review of the leading methods for the numerical solution of general electromagnetic problems is also included, but here the presentation aims at convincing the reader of high potential for complexity reduction and at further justifying and motivating the need for macromodeling.

Although the main focus of this book is on black-box macromodeling via system identification from external responses, complementary approaches are possible. In particular, Chapter 5 provides an overview of the prominent MOR techniques. These methods start with a large system of ODEs, for example, arising from a spatial discretization of field equations. Compact models are obtained through a projection or truncation process.

The subject of black-box macromodeling via data fitting is introduced in Chapter 6. After a general formulation, we review the various techniques that were widely used before the advent of the VF algorithm. Although the latter outperforms such preexisting techniques, we include a summary and some application examples, so that the advantages of VF are best understood, also from a historical perspective.

Chapter 7 is one of the core chapters of the book. A comprehensive presentation of the VF algorithm is included in frequency and time domains, applied to scalar single-input single-output systems. In addition to a formal development of the main scheme, several enhancements and implementation schemes are presented and discussed, with the help of various examples. Chapter 8 discusses instead the advanced features that make VF the method of choice for macromodel identification. These advanced features include several approaches for ensuring a good scalability with dynamic order and number of input/output ports.

Verification and enforcement of model passivity is fundamental to ensure the numerical stability of subsequent macromodel-based time-domain simulations. These two aspects are thoroughly discussed in Chapters 9 and 10. The former presents several passivity characterizations that are available for impedance, admittance, and scattering descriptions, based on either frequency-dependent or algebraic conditions. Building on these conditions and casting them as constraints, Chapter 10 presents various approaches for “correcting” a given macromodel by perturbing its parameters so that the final result is passive.

Once compact, accurate, and passive macromodels are available, they can be used in system-level transient simulations. Chapter 11 describes various approaches for including such macromodels within system-level simulation flows, either using out-of-the-box commercial solvers such as SPICE or EMTP-type tools or via direct numerical implementation.

Chapter 12 provides an overview of state-of-the-art macromodeling techniques for structures characterized by nonnegligible signal propagation delays between interface ports. Examples can be electrically long multiconductor transmission lines or even more complex interconnects including transmission line segments and discontinuities. Various approaches for extracting and including propagation delays in the macromodels are discussed and compared.

Finally, Chapter 13 presents a number of applications from different areas of engineering. Emphasis is on modeling and simulation of electromagnetic systems, ranging from high-frequency applications in microwave engineering, electromagnetic compatibility, and signal/power integrity, to low-frequency applications in power systems. The frequency responses of all such systems have quite similar features, even if geometry and frequency scales are different. These applications confirm the suitability of macromodels for efficient system simulation, both under normal operation conditions and during unexpected transients caused, for example, by unexpected disturbances or failures. We also include a few examples from nonelectrical disciplines, such as mechanical and hydraulic systems, demonstrating the interdisciplinary character of the techniques that are presented in the book.

SOME REMARKS ON NOTATION

Although a detailed list of symbols is provided in Appendix A, and each symbol is properly defined at its first occurrence, a few preliminary remarks are in order. Throughout this book, we denote scalar, vector, and matrix variables with x , $\mathbf{x}$, and $\mathbf{X}$, respectively. We denote with $\mathbf{X}^*$, $\mathbf{X}^T$, and $\mathbf{X}^H$ the complex conjugate, transpose, and conjugate (Hermitian) transpose, respectively, of a given matrix $\mathbf{X}$. The imaginary unit $j = \sqrt{-1}$ is denoted with an upright font and is not to be confused with the generic index j . The all-zero and identity matrices are denoted with $\mathbf{0}$ and $\mathbf{I}$, respectively. We will often need to construct matrices by stacking matrix blocks horizontally or vertically: the compact Matlab notation is used at times, with $(\mathbf{X}_1, \mathbf{X}_2)$ indicating a block-row matrix (i.e., $\mathbf{X}_2$ is placed at the right of $\mathbf{X}_1$), and $(\mathbf{X}_1; \mathbf{X}_2)$ indicating a block-column matrix (i.e., $\mathbf{X}_2$ is placed below $\mathbf{X}_1$). The set of all eigenvalues and singular values of $\mathbf{X}$ are denoted with $\lambda(\mathbf{X})$ and $\sigma(\mathbf{X})$, respectively.

The main focus of this book is on continuous-time, linear, time-invariant systems with a real-valued impulse response $\mathbf{h}(t)$. For these systems, we will generally use or derive state-space descriptions, with associated state-space matrices $\{\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}\}$. Most results are stated assuming that these state-space matrices are real-valued; the generalization to the complex-valued case is straightforward and not discussed in the book. Lowercase fonts are generally used to denote time-domain signals $\mathbf{x}(t)$, where t is time, whereas uppercase fonts describe their associated frequency-domain representation $\mathbf{X}(s)$, where s is the Laplace variable. Special signals (distributions) are the unit impulse or Dirac's delta $\delta(t)$, and the Heaviside unit step $\theta(t)$. A generic transfer matrix is denoted as $\mathbf{H}(s)$, and the corresponding impulse response matrix as $\mathbf{h}(t)$. Whenever the system under investigation is natively discrete-time, the corresponding signals will be denoted as $\mathbf{x}[k]$ or $\mathbf{x}_k$, where k is the discrete time index.

The use of accents is generally consistent throughout the book. With $\tilde{\mathbf{X}}$ we denote an alternative representation of $\mathbf{X}$, usually based on a transformation that is invertible (e.g., a similarity transformation between matrices). An overbar $\bar{\mathbf{X}}$ mostly describes a quantity derived from some inexact transformation (e.g., a matrix compression based on neglecting some small singular values, or a truncated Taylor series). A hat $\hat{\mathbf{X}}$ is used to indicate a quantity that is approximated, either via additive perturbation $\hat{\mathbf{X}} = \mathbf{X} + \Delta\mathbf{X}$ or via some discretization process. We include in the latter case quantities that are obtained from time discretization or numerical simulation of continuous-time systems, for example, $\hat{\mathbf{x}}_k \approx \mathbf{x}(t_k)$, where k is a discrete-time index. Finally, in the context of model extraction (Chapters 6–8), we denote with $\check{\mathbf{H}}(s)$ the response of the true (unknown) system or its discrete samples $\check{\mathbf{H}}_k \approx \check{\mathbf{H}}(s_k)$ available from a direct measurement or simulation. The corresponding model will be denoted by a bare symbol $\mathbf{H}(s)$.

The reader will soon realize that, in some cases, the same symbol or letter is used to denote more than one physical, geometrical, or mathematical entity. As an example, $\mathbf{C}$ can be used both as the per-unit-length capacitance matrix of a transmission line and as one of the state-space matrices of a linear dynamical system. We have struggled to resolve most of these ambiguities, but a few still remain. This is mainly because this book collects results from different disciplines (such as circuit and electromagnetic theory, system and control theory, system identification, and numerical analysis and optimization). Each of these disciplines has a quite consolidated “library” of standard symbols that are of common use, and conflicts are unavoidable. We believe, however, that this should not cause any confusion, since each symbol is properly defined and used with a unique meaning within the scope of a book unit (section or chapter).

ACKNOWLEDGMENTS

We owe a debt of gratitude to many colleagues, friends, students, and partners for many insightful discussions over the last few years. In particular, S.G.-T. would like to thank his colleagues of the EMC group at Politecnico di Torino, Prof. Flavio Canavero, Prof. Ivan Maio, and Prof. Igor Stievano, his former students Prof. Piero Triverio, Dr Andrea Ubolli, Dr Alessandro Chineza, Dr Bernardo Olivadese, Dr Haisheng Hu, as well as his collaborators Ing. Michelangelo Bandinu, Ing. Carla Giachino, and Dr Claudio Siviero for their precious contributions in several joint research tasks.

B.G. would in particular like to thank Prof. Emeritus Adam Semlyen at the University of Toronto, Canada, for his close cooperation and scientific input for nearly 20 years. Without the contributions from A.S., VF would not have materialized, and this book would not exist. B.G. also acknowledges the many useful discussions with colleagues Dr Thor Henriksen, Dr Andrzej Holdyk, and Magnar Hernes at SINTEF Energy Research, and Prof. Hans K. Høidalen at NTNU.

Both authors warmly acknowledge the many technical and sometimes challenging discussions with their colleagues at various institutions, with special mention to Prof. Michel Nakhla, Prof. Ram Achar, and Prof. Pavan Gunupudi (Carleton University, Ottawa, Canada), Prof. Roni Khazaka (McGill University, Montreal, Canada), Prof. Tom Dhaene, Prof. Dries Vande Ginste, and Dr Dirk Deschrijver (University of Gent, Belgium), Prof. Luca Daniel and Prof. Jacob White (MIT), Prof. Madhavan Swaminathan (Georgia Institute of Technology), Prof. Christian Schuster (Technical University Hamburg-Harburg, Germany), Prof. Jose Schutt-Ainé (University of Illinois), Prof. Andreas Weisshaar (Oregon State University), Prof. Abe Elfadel (Masdar Institute, UAE), Prof. Dipanjan Gope (Indian Institute of Science, Bangalore), Prof. Vikram Jandhyala (University of Washington), Dr Uwe Arz (PTB, Germany), Prof. Hartmut Grabinski (University of Hannover, Germany), Prof. Wil Schilders (TU Eindhoven, The Netherlands), John Nordstrom (The Manitoba HVDC Res. Center, Canada), Alvaro Portillo (WEG Transformers, Brazil), Prof. Jean Mahseredjian (Ecole Polytechnique de Montreal, Canada), Prof. Juan Martinez-Velasco (UPC, Spain), Prof. Reza Iravani, (University of Toronto, Canada), Prof. Ani Gole (University of Manitoba, Canada), Prof. Marjan Popov (Delft University of Technology, Netherlands), Garth Irwin and Dennis Woodford (Electranix, Canada), and Prof. Bruce Mork (Michigan Technical University, USA).

S.G.-T. is particularly grateful to the industrial partners that supported his research in the field of macromodeling, including IBM (E. Klink, G. Katopis, A. Deutsch, B. Rubin, A. Ruehli, J. Morsey, D. Becker, D. Kaller, and many others), NOKIA (I. Kelander, M. Rouvala), Hitachi (Y. Uematsu), and to the EDA partners Zuken, E-System Design, Nimbic, and of course IdemWorks.

B.G. especially thanks SINTEF Energy Research for its support during the writing of this book. Substantial support was also received from the Norwegian Research Council and the following industrial partners within the project “EM Transients”: DONG Energy (Ivan Arana and Lukasz Kocewiak), EdF (Alain Xemard), EirGrid (Andrea Mansoldo), Hafslund Nett (Hugo W. Thøgersen), National Grid Electricity Transmission (Forooz Ghassemi), Nexans Norway (Ronny Stølan), RTE (Yannick Vernay), SIEMENS WP (John Bech), Statkraft (Bjørn Tandstad), Statnett (Trond Ohnstad), and Vestas WS (Philip Carne Kjær). The cooperation with the staff at Manitoba HVDC Research Centre is also appreciated.

STEFANO GRIVET-TALOCIA
BJØRN GUSTAVSEN

CONTENTS

Preface

xix

1 Introduction

1

- 1.1 Why Macromodeling?, 1
- 1.2 Scope, 4
- 1.3 Macromodeling Flows, 6
 - 1.3.1 Macromodeling via Model Order Reduction, 6
 - 1.3.2 Macromodeling from Field Solver Data, 7
 - 1.3.3 Macromodeling from Measured Responses, 8
- 1.4 Rational Macromodeling, 9
- 1.5 Physical Consistency Requirements, 11
- 1.6 Time-Domain Implementation, 15
- 1.7 An Example, 16
- 1.8 What Can Go Wrong?, 17

2 Linear Time-Invariant Circuits and Systems

23

- 2.1 Basic Definitions, 24
 - 2.1.1 Linearity, 24
 - 2.1.2 Memory and Causality, 26
 - 2.1.3 Time Invariance, 26
 - 2.1.4 Stability, 27
 - 2.1.5 Passivity, 28
- 2.2 Linear Time-Invariant Systems, 28
 - 2.2.1 Impulse Response, 29
 - 2.2.2 Properties of LTI Systems, 32

- 2.3 Frequency-Domain Characterizations, 33
- 2.4 Laplace and Fourier Transforms, 34
 - 2.4.1 Bilateral Laplace Transform and Transfer Matrices, 34
 - 2.4.2 Causal LTI Systems and the Unilateral Laplace Transform, 36
 - 2.4.3 Fourier Transform, 36
- 2.5 Signal and System Norms*, 37
 - 2.5.1 Signal Norms, 38
 - 2.5.2 System Norms, 41
- 2.6 Multiport Representations, 44
 - 2.6.1 Ports and Terminals, 44
 - 2.6.2 Immittance Representations, 45
 - 2.6.3 Scattering Representations, 46
 - 2.6.4 Reciprocity, 48
- 2.7 Passivity, 49
 - 2.7.1 Power and Energy, 50
 - 2.7.2 Passivity and Causality, 51
 - 2.7.3 The Static Case, 52
 - 2.7.4 The Dynamic Case, 53
 - 2.7.5 Positive Realness, Bounded Realness, and Passivity, 54
 - 2.7.6 Some Examples, 56
- 2.8 Stability and Causality, 59
 - 2.8.1 Laplace-Domain Conditions for Causality, 61
 - 2.8.2 Laplace-Domain Conditions for BIBO Stability, 62
 - 2.8.3 Causality and Stability, 62
- 2.9 Boundary Values and Dispersion Relations*, 64
 - 2.9.1 Assumptions, 64
 - 2.9.2 Reconstruction of $H(s)$ for $s \in \mathbb{C}_+$, 65
 - 2.9.3 Reconstruction of $H(s)$ for $s \in j\mathbb{R}$, 65
 - 2.9.4 Causality and Dispersion Relations, 67
 - 2.9.5 Generalizations, 68
- 2.10 Passivity Conditions on the Imaginary Axis*, 70
 - Problems, 71

3 Lumped LTI Systems

73

- 3.1 An Example from Circuit Theory, 74
 - 3.1.1 Variation on a Theme, 76
 - 3.1.2 Driving-Point Impedance, 77
- 3.2 State-Space and Descriptor Forms, 77
 - 3.2.1 Singular Descriptor Forms, 77
 - 3.2.2 Internal Representations of Lumped LTI Systems, 79
- 3.3 The Zero-Input Response, 80
- 3.4 Internal Stability, 81
 - 3.4.1 Lyapunov Stability, 81
 - 3.4.2 Internal Stability of LTI Systems, 83
- 3.5 The Lyapunov Equation, 84

- 3.6 The Zero-State Response, 87
 - 3.6.1 Impulse Response, 88
- 3.7 Operations on State-Space Systems, 89
 - 3.7.1 Interconnections, 90
 - 3.7.2 Inversion, 91
 - 3.7.3 Similarity Transformations, 91
- 3.8 Gramians, 91
 - 3.8.1 Observability, 92
 - 3.8.2 Controllability, 93
 - 3.8.3 Minimal Realizations, 95
- 3.9 Reciprocal State-Space Systems, 95
- 3.10 Norms, 97
 - 3.10.1 $\mathcal{L}_2$ Norm, 98
 - 3.10.2 $\mathcal{H}_\infty$ Norm, 99
- Problems, 100

4 Distributed LTI Systems

103

- 4.1 One-Dimensional Distributed Circuits, 104
 - 4.1.1 The Discrete-Space Case, 104
 - 4.1.2 The Continuous-Space Case, 106
 - 4.1.3 Discussion, 109
- 4.2 Two-Dimensional Distributed Circuits*, 111
 - 4.2.1 The Discrete-Space Case, 112
 - 4.2.2 The Continuous-Space Case, 114
 - 4.2.3 A Closed-Form Solution, 116
 - 4.2.4 Spatial Discretization, 118
 - 4.2.5 Discussion, 120
- 4.3 General Electromagnetic Characterization, 123
 - 4.3.1 3D Electromagnetic Modeling, 126
 - 4.3.2 Summary and Outlook, 130
- Problems, 131

5 Macromodeling Via Model Order Reduction

135

- 5.1 Model Order Reduction, 135
- 5.2 Moment Matching, 136
 - 5.2.1 Moments, 136
 - 5.2.2 Padé Approximation and AWE, 138
 - 5.2.3 Complex Frequency Hopping, 139
- 5.3 Reduction by Projection, 140
 - 5.3.1 Krylov Subspaces, 141
 - 5.3.2 Implicit Moment Matching: The Orthogonal Case, 142
 - 5.3.3 The Arnoldi Process, 143
 - 5.3.4 PRIMA, 145
 - 5.3.5 Multipoint Moment Matching, 147
 - 5.3.6 An Example, 148

- 5.3.7 Implicit Moment Matching: The Biorthogonal Case, 151
- 5.3.8 Padé Via Lanczos (PVL), 154
- 5.4 Reduction by Truncation, 155
 - 5.4.1 Balancing, 156
 - 5.4.2 Balanced Truncation, 158
- 5.5 Advanced Model Order Reduction*, 159
 - 5.5.1 Passivity-Preserving Balanced Truncation, 159
 - 5.5.2 Balanced Truncation of Descriptor Systems, 160
 - 5.5.3 Reducing Large-Scale Systems, 161
- Problems, 166

6 Black-Box Macromodeling and Curve Fitting

169

- 6.1 Basic Curve Fitting, 171
 - 6.1.1 Linear Least Squares, 172
 - 6.1.2 Maximum Likelihood Estimation, 174
 - 6.1.3 Polynomial Fitting, 176
- 6.2 Direct Rational Fitting, 182
 - 6.2.1 Polynomial Ratio Form, 183
 - 6.2.2 Pole–Zero Form, 183
 - 6.2.3 Partial Fraction Form, 184
 - 6.2.4 Partial Fraction Form with Fixed Poles, 184
 - 6.2.5 Nonlinear Least Squares, 185
- 6.3 Linearization via Weighting, 187
- 6.4 Asymptotic Pole–Zero Placement, 191
- 6.5 ARMA Modeling, 193
 - 6.5.1 Modeling from Time-Domain Responses, 195
 - 6.5.2 Modeling from Frequency Domain Responses, 197
 - 6.5.3 Conversion of ARMA Models, 201
- 6.6 Prony's Method, 203
- 6.7 Subspace-Based Identification*, 204
 - 6.7.1 Discrete-Time State-Space Systems, 204
 - 6.7.2 Macromodeling from Impulse Response Samples, 205
 - 6.7.3 Macromodeling from Input–Output Samples, 207
 - 6.7.4 From Discrete-Time to Continuous-Time State-Space Models, 210
 - 6.7.5 Frequency-Domain Subspace Identification, 211
 - 6.7.6 Generalized Pencil-of-Function Methods, 212
 - 6.7.7 Examples, 214
- 6.8 Loewner Matrix Interpolation*, 215
 - 6.8.1 The Scalar Case, 216
 - 6.8.2 The Multiport Case, 218
- Problems, 222

7 The Vector Fitting Algorithm

225

- 7.1 The Sanathanan–Koerner Iteration, 226
 - 7.1.1 The Steiglitz–McBride Iteration, 229

- 7.2 The Generalized Sanathanan–Koerner Iteration, 231
 - 7.2.1 General Basis Functions, 231
 - 7.2.2 The Partial Fraction Basis, 233
 - 7.3 Frequency-Domain Vector Fitting, 234
 - 7.3.1 A Simple Model Transformation, 234
 - 7.3.2 Computing the New Poles, 236
 - 7.3.3 The Vector Fitting Iteration, 237
 - 7.3.4 From GSK to VF, 239
 - 7.4 Consistency And Convergence, 241
 - 7.4.1 Consistency, 241
 - 7.4.2 Convergence, 242
 - 7.4.3 Formal Convergence Analysis, 245
 - 7.5 Practical VF Implementation, 247
 - 7.5.1 Causality, Stability, and Realness, 247
 - 7.5.2 Order Selection and Initialization, 253
 - 7.5.3 Improving Numerical Robustness, 254
 - 7.6 Relaxed Vector Fitting, 256
 - 7.6.1 Weight Normalization, Noise, and Convergence, 256
 - 7.6.2 Relaxed Vector Fitting, 259
 - 7.7 Tuning VF, 264
 - 7.7.1 Weighting and Error Control, 264
 - 7.7.2 High-Frequency Behavior, 266
 - 7.7.3 High-Frequency Constraints, 268
 - 7.7.4 DC Point Enforcement, 269
 - 7.7.5 Simultaneous Constraints, 271
 - 7.8 Time-Domain Vector Fitting, 273
 - 7.9 z-Domain Vector Fitting, 278
 - 7.10 Orthonormal Vector Fitting, 281
 - 7.10.1 Orthonormal Rational Basis Functions, 281
 - 7.10.2 The OVF Iteration, 284
 - 7.10.3 The OVF Pole Relocation Step, 285
 - 7.10.4 Finding Residues, 286
 - 7.11 Other Variants, 288
 - 7.11.1 Magnitude Vector Fitting, 288
 - 7.11.2 Vector Fitting with $\mathcal{L}_1$ Norm Minimization, 291
 - 7.11.3 Dealing with Higher Pole Multiplicities, 293
 - 7.11.4 Including Higher Order Derivatives, 294
 - 7.11.5 Hard Relocation of Poles, 295
 - 7.12 Notes on Overfitting and Ill-Conditioning, 296
 - 7.12.1 Exact Model Identification, 296
 - 7.12.2 Curve Fitting, 297
 - 7.13 Application Examples, 299
 - 7.13.1 Surface Acoustic Wave Filter, 299
 - 7.13.2 Subnetwork Equivalent, 301
 - 7.13.3 Transformer Modeling from Time-Domain Measurements, 303
- Problems, 303