Nonlinear Approaches in Engineering Applications

Liming Dai • Reza N. Jazar
Editors

Nonlinear Approaches in Engineering Applications

Editors

Liming Dai
Industrial Systems Engineering
University of Regina
Regina, SK, Canada
liming.dai@uregina.ca

Reza N. Jazar
School of Aerospace, Mechanical,
and Manufacturing Engineering
RMIT University
Melbourne, VIC, Australia
reza.jazar@rmit.edu.au

ISBN 978-1-4614-1468-1 e-ISBN 978-1-4614-1469-8

DOI 10.1007/978-1-4614-1469-8

Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2011942901

© Springer Science+Business Media, LLC 2012

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

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

Dedicated to our wives Xinming and Mojgan

*Being smart means: do not keep your
smartness at the level that is needed for
your job*

Preface

The initiation of this book started with the discussions in the ASME 2010 and 2009 Congress in the track of Dynamics Systems and Control, Optimal Approaches in Nonlinear Dynamics and Acoustics, which were organized by the editors. Since the 1980s, many new nonlinear approaches and techniques have been developed and the research on nonlinear science and dynamics have brought new insights in our dealing with nonlinear and complex systems in nature, engineering, and society. Although more and more such approaches and techniques have been brought into research and engineering practices, linearization and simplification are still the dominating approaches existing in physics and engineering. Strictly and precisely speaking, our nature is nonlinear. All the phenomena in nature and all the responses of physics and engineering systems are nonlinear. Linearization means simplification, and it damages the original natural or characteristics of the systems and may lead to inaccuracy, misunderstanding, or even incorrect conclusions in comprehending the physics and engineering systems we are trying to manage. Hooke's law including the generalized Hooke's law, for example, is linear and it composes the foundation of linear elasticity and dominates numerous solutions of physical systems and mechanical designs. However, no material is perfectly linear. Although most plain carbon steels are considered as materials obey Hooke's law in engineering practice, for instance, it is a common knowledge to the material scientists these materials are nonlinear and the constitutive relations of the materials are close to a nonlinear polynomial of third or fifth order. Any single material used in the real world can actually be a nonlinear and complex system, not only due to its material or structure nonlinearity but also due to the inhomogeneousness and anisotropy of the materials, let alone the associated complex external loading and large deformation which may occur in many engineering cases. With the explosively growing body of knowledge and discoveries in nonlinear science, obviously, we are entering an era that nonlinearity and complexity must be taken into consideration in coping with physical and engineering systems in real world.

Another challenge facing the scientists and engineers in our time is the generation of the solutions and characterization of the nonlinear systems modeled from the physical systems in reality. It would be greatly beneficial in accurately

evaluating the behavior of nonlinear systems and revealing the actual nature of the systems, with utilization of the existing mathematical tools and analytical means, if the analytical solutions of nonlinear systems could be pursued. Due to the nonlinearity and complexity of the nonlinear systems, unfortunately, it is very difficult or impossible to derive the analytical or closed-loop solutions for the systems. In solving or simulating the nonlinear systems, one may have to rely on approximate or numerical methods, which may only provide approximate results for the systems while errors are unavoidable during the processes of generating the approximate results. Approximation and inaccuracy are the inescapable shadows following the current research and engineering practices involving nonlinearity or nonlinear systems.

In the role of the editors as well as the chapter contributors of this book, we have tried to present a collection of chapters showing the theoretically and practically sound nonlinear approaches and their engineering applications in various areas, hoping that this book may provide useful tools and comprehensible examples of solving, modeling, and simulating the nonlinear systems existing in the real world. The carefully selected chapters contained in the present book reflect recent advances in nonlinear approaches and their engineering applications. The book intends to feature in particular the fundamental concepts and approaches of nonlinear science and their applications in engineering and physics fields. It is anticipated that this book may help to promote the development of nonlinear science and nonlinear dynamics in engineering, as well as to stimulate research and applications of nonlinear science and nonlinear dynamics in physics and engineering practices. It is also expected that the book will further enhance the comprehension of nonlinear science and stimulate interactions among scientists and engineers who are interested in nonlinear science and who find that nonlinearity and complexity of systems play an important role in their respective fields.

With the theme of the book, nonlinear approaches and engineering applications, the book covers interdisciplinary studies on theories and methods of nonlinear science and their applications in complex systems such as those in nonlinear dynamics, nanotechnology, fluid dynamics, aerospace structure engineering, mechatronics engineering, control engineering, ocean engineering, offshore structure engineering, mechanical engineering, human body dynamics, and material science. Examples include innovative methodology of diagnosing nonlinear characteristics; approach of modeling squeeze-film phenomena in *MEMS*; nonlinear modeling of microbeams; new and explicit equations of motion for general nonlinear constrained mechanical systems; study on nonlinear dynamic behaviors of a Fermi oscillator with two periodic excitations; development of active surface control (ASC) architecture for deployable mesh reflectors to be used for satellite communications; nonlinear finite elements approach for modeling nano- and macroscale beam-like materials and structures; approach of modeling a submerged rigid body supported by slack moorings; study on linear and nonlinear viscoelastic materials in terms of constitutive equations, stress relaxation, and strain rate dependency; investigation on the nonlinear hysteresis effect in electromechanical brakes; energy conservative design and nonlinear control of a hopping robot; study on nonlinear and complex

flow around a cylinder; vibration of truncated conical shells; image-based pose estimation of quadrotor unmanned aerial vehicle (UAV); and nonlinear modeling of head-neck complex system.

Level of the Book

This book aims at engineers, scientists, researchers, engineering and physics students of undergraduate and graduate levels, together with the interested individuals in engineering, physics, and mathematics. This chapter-book focuses on application of the nonlinear approaches representing a wide spectrum of disciplines of engineering and science. Throughout the book, great emphases are placed on engineering applications, physical meaning of the nonlinear systems, and methodologies of the approaches in analyzing and solving for the systems. Topics that have been selected are of high interest in engineering and physics. An attempt has been made to expose the engineers and researchers to a broad range of practical topics and approaches.

The topics contained in the present book are of specific interest to engineers who are seeking expertise in nonlinear analysis, mathematical modeling of complex systems, optimization of nonlinear systems, nonclassical engineering problems, and future of engineering.

The primary audience of this book is the researchers, graduate students and engineers in mechanical engineering, engineering mechanics, civil engineering, aerospace engineering, ocean engineering, mathematics, and science disciplines. In particular, the book can be used as a textbook for the graduate students as well as senior undergraduate students to enhance their knowledge by taking a graduate or advanced undergraduate course in the areas of nonlinear science, dynamics and vibration of continuous system, structure dynamics, and engineering applications of nonlinear science. It can also be utilized as a guide to the readers' fulfillment in practices. The covered topics are also of interest to engineers who are seeking to expand their expertise in these areas.

Organization of the Book

The main structure of the book consists of 15 chapters. Each of the chapters covers an independent topic along the line of nonlinear approach and engineering applications of nonlinear science. The main concepts in nonlinear science and engineering applications are explained fully with necessary derivatives in details. The book and each of the chapters are intended to be organized as essentially self-contained. All necessary concepts, proofs, mathematical background, solutions, methodologies, and references are supplied except for some fundamental knowledge well-known in the general fields of engineering and physics. The readers may

therefore gain the main concepts of each chapter with as less as possible the need to refer to the concepts of the other chapters. Readers may hence start to read one or more chapters of the book for their own interests.

Method of Presentation

The scope of each chapter is clearly outlined and the governing equations are derived with an adequate explanation of the procedures. The covered topics are logically and completely presented without unnecessary overemphasis. The topics are presented in a book form rather than in the style of a handbook. Tables, charts, equations, and references are used in abundance. Proofs and derivations are emphasized in such a way that they can be straightforwardly followed by the readers with fundamental knowledge of engineering science and university physics. The physical model and final results provided in the chapters are accompanied with necessary illustrations and interpretations. Specific information that is required in carrying out the detailed theoretical concepts and modelling processes has been stressed.

Prerequisites

The present book is primarily intended for researchers, engineers, and graduate students, so the assumption is that the readers are familiar with the fundamentals of dynamics, calculus, and differential equations associated with dynamics in engineering and physics, as well as a basic knowledge of linear algebra and numerical methods. The presented topics are given in a way to establish as conceptual framework that enables the readers to pursue further advances in the field. Although the governing equations and modelling methodologies will be derived with adequate explanations of the procedures, it is assumed that the readers have a working knowledge of dynamics, university mathematics, and physics together with theory of linear elasticity.

Acknowledgments

This book is made available under the close and effective collaborations of all the enthusiastic chapter contributors who have the expertise and experience in various disciplines of nonlinear science and engineering applications. They deserve sincere gratitude for the motivation of creating such book, encouragement in completing the book, scientific and professional attitude in constructing each of the chapters of the book, and the continuous efforts toward improving the quality of the book. Without the collaboration and consistent efforts of the chapter contributors, the completion

of this book would have been impossible. What we have at the end is a book that we have every reason to be proud of.

It has been gratifying to work with the staff of Springer-Verlag through the development of this book. The assistances provided by the staff members have been valuable and efficient. We thank Springer-Verlag for their production of an elegant book.

Regina, SK, Canada
Melbourne, VIC, Australia

Liming Dai
Reza N. Jazar

Contents

1	Characterizing Nonlinear Dynamic Systems	1
	Liming Dai and Lu Han	
2	Nonlinear Modeling of Squeeze-Film Phenomena	41
	Reza N. Jazar	
3	Nonlinear Mathematical Modeling of Microbeam MEMS	69
	Reza N. Jazar	
4	Complex Motions in a Fermi Oscillator.....	105
	Yu Guo and Albert C.J. Luo	
5	Nonlinear Visco-Elastic Materials	135
	Franz Konstantin Fuss	
6	Nonlinear Dynamic Modeling of Nano and Macroscale Systems	171
	Michael J. Leamy	
7	Equilibrium of a Submerged Body with Slack Mooring	211
	Brian C. Fabien	
8	Nonlinear Deployable Mesh Reflectors.....	237
	Hang Shi and Bingen Yang	
9	Nonlinearity in an Electromechanical Braking System	265
	Reza Hoseinnezhad and Alireza Bab-Hadiashar	
10	Nonlinear Dynamics of Incompressible Flow.....	283
	Jiazhong Zhang	
11	Explicit Equation of Motion of Constrained Systems	315
	Firdaus E. Udwadia and Thanapat Wanichanon	
12	Nonlinear Dynamic of a Rotating Truncated Conical Shell	349
	Changping Chen	

13 Nonlinear Real-Time Pose Estimation of Quadrotor UAV 393
Chayatat Ratanasawanya, Mehran Mehrandezh, and Raman
Paranjape

**14 Energy Conservative Design and Nonlinear Control of
Balance in a Hopping Robot..... 421**
Klaus Nji and Mehran Mehrandezh

15 Nonlinearities in Human Body Dynamics 475
M. Fard, Y. Ohtaki, T. Ishihara, and H. Inooka

Index 525

List of Figures

Fig. 1.1	Procedures of Periodicity Ratio determination	10
Fig. 1.2	Procedures of statistical hypothesis testing	11
Fig. 1.3	Bar chart for the distribution of different categories of motion under different given overlapping boundaries.....	17
Fig. 1.4	Poincare map at $k = 0.6$ and $B = 10.6$	21
Fig. 1.5	Phase diagram at $k = 0.6$ and $B = 10.6$	22
Fig. 1.6	Poincare map at $k = 0.15$ and $B = 7.2$	22
Fig. 1.7	Phase diagram at $k = 0.15$ and $B = 7.2$	23
Fig. 1.8	Poincare map at $k = 0$ and $B = 7$	23
Fig. 1.9	Quasiperiodic phase diagram at $k = 0$ and $B = 7$	23
Fig. 1.10	Poincare map at $k = 0.81$ and $B = 0.02$	24
Fig. 1.11	Phase diagram at $k = 0.81$ and $B = 0.02$	24
Fig. 1.12	Poincare map of a nonperiodic case at $k = 0.37$ and $B = 8.9$	25
Fig. 1.13	Phase diagram at $k = 0.37$ and $B = 8.9$	25
Fig. 1.14	Poincare map of a nonperiodic motion at $k = 0.09$ and $B = 11.9$	27
Fig. 1.15	Poincare map of a nonperiodic motion at $k = 0.09$ and $B = 11.9$	27
Fig. 1.16	Poincare map at $k = 0.68$ and $B = 5.3$	28
Fig. 1.17	Phase diagram at $k = 0.68$ and $B = 5.3$	28
Fig. 1.18	Critical region diagram of binomial distribution	30
Fig. 1.19	Periodic–quasiperiodic–chaotic diagram for Duffing system under given overlapping boundary of 10^{-7}	32
Fig. 1.20	Periodic–quasiperiodic–chaotic diagram for Duffing system under given overlapping boundary 10^{-3}	33
Fig. 1.21	Periodic–quasiperiodic–chaotic diagram for Duffing system under given overlapping boundary of 10^{-8}	34
Fig. 1.22	Periodicities of the responses of Duffing system under the given overlapping boundary of 10^{-7}	34

Fig. 1.23	Three-dimensional periodic–quasiperiodic–chaotic diagram for Duffing system	35
Fig. 1.24	Phase diagram at $k = 0.17$, $B = 10$, and $PR = 1$	36
Fig. 1.25	Phase diagram at $k = 0.16$, $B = 10$, and $PR = 0.3127$	36
Fig. 1.26	Phase diagram at $k = 0.15$, $B = 10$, and $PR = 0.0403$	36
Fig. 1.27	Phase diagram at $k = 0.14$, $B = 10$, and $PR = 0.0$	37
Fig. 2.1	A microcantilever resonator and resistance of the pressurized gas	43
Fig. 2.2	A microcantilever and a clamped-clamped model of microresonator to keep the capacitor's plates parallel	46
Fig. 2.3	Effect of variation of polarization voltage on frequency response of the microbeam	56
Fig. 2.4	Effect of variation of polarization voltage on frequency response of the microbeam	57
Fig. 2.5	Effect of variation of polarization voltage on frequency response of the microbeam	57
Fig. 2.6	Effect of variation of polarization voltage on frequency response of the microbeam	58
Fig. 2.7	Effect of variation of excitation voltage on frequency response of the microbeam	58
Fig. 2.8	Effect of variation of excitation voltage on frequency response of the microbeam	59
Fig. 2.9	Effect of variation of excitation voltage on frequency response of the microbeam	59
Fig. 2.10	Effect of variation of excitation voltage on frequency response of the microbeam	60
Fig. 2.11	Effect of variation of squeeze-film damping on frequency response of the microbeam	60
Fig. 2.12	Effect of variation of squeeze-film damping on frequency response of the microbeam	61
Fig. 2.13	Effect of variation of squeeze-film damping on frequency response of the microbeam	61
Fig. 2.14	Effect of variation of squeeze-film damping on frequency response of the microbeam	62
Fig. 2.15	Equivalent linear damping and stiffness as a function of frequency and squeeze-film damping and stiffness coefficients	62
Fig. 2.16	Equivalent linear damping and stiffness as a function of frequency and squeeze-film damping and stiffness coefficients	63
Fig. 3.1	A clamped– clamped model of a <i>MEMS</i> and its voltage connections	73
Fig. 3.2	A clamped– clamped model of a <i>MEMS</i> to keep the capacitor's plates parallel	73
Fig. 3.3	Various examples of connecting a microbeam to the ground	74

Fig. 3.4	Alternative examples of connecting a microbeam to the ground ...	74
Fig. 3.5	A microcantilever-based MEMS	83
Fig. 3.6	Effect of the variation of excitation and polarization voltages on peak amplitude at resonance	95
Fig. 3.7	Effect of the variation of excitation and polarization voltages on peak amplitude at resonance	95
Fig. 3.8	Effect of the variation of excitation and polarization voltages on peak amplitude at resonance	96
Fig. 3.9	Effect of the variation of excitation and polarization voltages on peak amplitude at resonance	96
Fig. 3.10	Equivalent linear damping and stiffness as a function of frequency and squeeze-film damping and stiffness coefficients	99
Fig. 3.11	Equivalent linear damping and stiffness as a function of frequency and squeeze-film damping and stiffness coefficients	99
Fig. 4.1	Mechanical model of Fermi oscillator	106
Fig. 4.2	Absolute domains and boundaries without stick: (a) Bottom oscillator, (b) top oscillator, and (c) particle	107
Fig. 4.3	Absolute domains and boundaries with stick: (a) bottom oscillator, (b) top oscillator, and (c) particle	109
Fig. 4.4	Domains and boundaries definition relative to the bottom oscillator: (a) $(z, \dot{z})$ -plane for bottom oscillator, (b) $(z, \dot{z})$ -plane for bottom oscillator, (c) -plane for particle, and (d) $(z, \dot{z})$ -plane for particle	110
Fig. 4.5	Domains and boundaries definition relative to the top oscillator: (a) -plane for top oscillator, (b) $(z, \dot{z})$ -plane for top oscillator, (c) $(z, \dot{z})$ -plane for particle, and (d) $(z, \dot{z})$ -plane for particle	111
Fig. 4.6	Switching sets and generic mappings for nonstick motion in absolute coordinates: (a) bottom oscillator, (b) top oscillator, and (c) particle	117
Fig. 4.7	Switching sets and generic mappings for stick motion in absolute coordinates: (a) bottom oscillator, (b) top oscillator, and (c) particle	118
Fig. 4.8	Bifurcation scenario of varying restitution coefficient: (a) displacement of particle, (b) velocity of particle, and (c) switching phase. ($Q^{(1)} = Q^{(2)} = 12.0$, $\Omega^{(2)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1$, $0, m^{(3)} = 0.01$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$)	123
Fig. 4.9	Analytical prediction of varying the restitution coefficient of impact: (a) switching displacement of particle, (b) switching velocity of particle; (c) switching phase. ($Q^{(1)} = Q^{(2)} = 12.0$, $\Omega^{(2)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1$, $0, m^{(3)} = 0.01$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$)	124

- Fig. 4.10 Zoomed Analytical prediction of varying the restitution coefficient of impact: **(a)** switching displacement of particle, **(b)** switching velocity of particle; **(c)** switching phase. ($Q^{(1)} = Q^{(2)} = 12.0$, $\Omega^{(2)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1, 0$, $m^{(3)} = 0.01$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$) 125
- Fig. 4.11 Zoomed Analytical prediction of varying the restitution coefficient of impact: **(a)** real part of eigenvalues, **(b)** imaginary part of eigenvalues, and **(c)** magnitude of eigenvalues. ($Q^{(1)} = Q^{(2)} = 12.0$, $\Omega^{(2)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1, 0$, $m^{(3)} = 0.01$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$) 126
- Fig. 4.12 Analytical prediction of varying the restitution coefficient of impact: **(a)** real part of eigenvalues, **(b)** imaginary part of eigenvalues, and **(c)** magnitude of eigenvalues. ($Q^{(1)} = Q^{(2)} = 12.0$, $\Omega^{(2)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1, 0$, $m^{(3)} = 0.01$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$) 128
- Fig. 4.13 Periodic motion: **(a)** displacement time history, **(b)** velocity time history, and **(c)** trajectory of particle with moving boundaries. ($Q^{(1)} = Q^{(2)} = 12.0$, $\Omega^{(1)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1, 0$, $m^{(3)} = 0.01$, $e^{(1)} = e^{(2)} = 0.1$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$). Initial conditions: $x_0^{(1)} = x_0^{(3)} = -0.5575740$, $\dot{x}_0^{(1)} = \dot{x}_0^{(3)} = 1.5959726$, $x_0^{(2)} = -0.0613454$, $\dot{x}_0^{(2)} = 1.6725197$ for $t_0 = 0.0227104$ 129
- Fig. 4.14 Periodic motion: **(a)** acceleration along displacement, **(b)** acceleration time history and **(c)** jerk time history. ($Q^{(1)} = Q^{(2)} = 12.0$, $\Omega^{(1)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1, 0$, $m^{(3)} = 0.01$, $e^{(1)} = e^{(2)} = 0.1$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$). Initial conditions: $x_0^{(1)} = x_0^{(3)} = -0.5575740$, $\dot{x}_0^{(1)} = \dot{x}_0^{(3)} = 1.5959726$, $x_0^{(2)} = -0.0613454$, $\dot{x}_0^{(2)} = 1.6725197$ for $t_0 = 0.0227104$ 130

- Fig. 4.15 Chaotic motion: **(a)** displacement time history, **(b)** velocity time history, **(c)** Poincare map of $(x_k^{(3)}, y_k^{(3)})$. ($Q^{(1)} = Q^{(2)} = 20.0$, $\Omega^{(1)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1.0$, $m^{(3)} = 0.01$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$). The initial conditions are $x_0^{(1)} = 0.941968193$, $\dot{x}_0^{(1)} = 1.86109613$, $x_0^{(2)} = x_0^{(3)} = 1.45709118$, $\dot{x}_0^{(2)} = 1.82722043$, and $\dot{x}_0^{(3)} = 10.7134817$ for $t_0 = 0.289711605$ 131
- Fig. 4.16 Chaotic motion: **(a)** Poincare map of $(x_k^{(4)}, y_k^{(4)})$, **(b)** Poincare map of $(x_k^{(3)} \bmod (\Omega t_h, 2h))$, and **(c)** Poincare map of $(y_k^{(3)} \bmod (\Omega t_h, 2h))$. ($Q^{(1)} = Q^{(2)} = 20.0$, $\Omega^{(1)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1.0$, $m^{(3)} = 0.01$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$). The initial conditions are $x_0^{(1)} = 0.941968193$, $\dot{x}_0^{(1)} = 1.86109613$, $x_0^{(2)} = x_0^{(3)} = 1.45709118$, $\dot{x}_0^{(2)} = 1.82722043$, and $\dot{x}_0^{(3)} = 10.7134817$ for $t_0 = 0.289711605$ 132
- Fig. 4.17 Parameter map ($\Omega^{(1)} = \Omega^{(2)} = 10.0$, $m^{(1)} = m^{(2)} = 1.0$, $m^{(3)} = 0.01$, $h = 0.5$, $k^{(1)} = k^{(2)} = 80.0$, $c^{(1)} = c^{(2)} = 0.1$) 133
- Fig. 5.1 Linear visco-elastic models; **(a)** Zener model (standard linear solid of Voight form), **(b)** standard linear solid of Maxwell form, **(c)** Wiechert model (generalised Maxwell model, note that the first damper η_1 is rigid) 137
- Fig. 5.2 Stress relaxations of power and logarithmic models, as well as of Maxwell standard linear solid (MSLS) on a graph with linear axes 141
- Fig. 5.3 Stress relaxations of power and logarithmic models, as well as of Maxwell standard linear solid (MSLS) on a single-log graph 141
- Fig. 5.4 Stress relaxations of power and logarithmic models, as well as of Maxwell standard linear solid (MSLS) on a double-log graph 142
- Fig. 5.5 Ramp strain followed by constant strain. Δt = time period of the ramp segment, ε_0 = maximal strain applied 144

Fig. 5.6	Stress relaxations of power and logarithmic models, as well as of Maxwell (MSLS) on a single-log graph; bold curves: relaxation after applying a Heaviside strain function, dashed curves = family of stress relaxations after applying a ramp and constant strain according to Fig. 5.5 and (5.31).....	145
Fig. 5.7	Stress relaxations of power and logarithmic models, as well as of Maxwell (MSLS) on a single-log graph; dashed curves = family of stress relaxations after applying a ramp and constant strain according to Fig. 5.5 and (5.31).....	146
Fig. 5.8	Stress relaxations of power and logarithmic models, as well as of Maxwell (MSLS) on a double-log graph; bold curves: relaxation after applying a Heaviside strain function, dashed curves = family of stress relaxations after applying a ramp and constant strain according to Fig. 5.5 and (5.31).....	147
Fig. 5.9	Stress relaxations of power and logarithmic models, as well as of Maxwell (MSLS) on a double-log graph; dashed curves = family of stress relaxations after applying a ramp and constant strain according to Fig. 5.5 and (5.31).....	148
Fig. 5.10	Stress relaxations of power model and Wiechert model (Prony series 1, (5.36)–(5.39)) after Heaviside strain function	149
Fig. 5.11	Stress relaxations of power model and Wiechert model (Prony series 2, (5.42)–(5.45)) after applying a ramp and constant strain according to Fig. 5.5 and (5.31); * = stress increasing with ramp strain	150
Fig. 5.12	Power model ($R = 10$, $\eta = 0.3$) at different strain rates ($1.667s^{-1}$, $2.5s^{-1}$, $5s^{-1}$): stress against strain (loading and unloading segment; three stress values at 0.4 strain are marked)	156
Fig. 5.13	Power model ($R = 10$, $\eta = 0.3$) at different strain rates ($1.667s^{-1}$, $2.5s^{-1}$, $5s^{-1}$); modulus against strain (loading only)	156
Fig. 5.14	Power model ($R = 10$, $\eta = 0.3$) at different strain rates ($1.667s^{-1}$, $2.5s^{-1}$, $5s^{-1}$); three log modulus values at 0.4 strain against $\ln \dot{\epsilon}_0/\epsilon$, linear fit with intercept at $\ln 10$ and gradient of 0.3	157
Fig. 5.15	Calculation of parameters from Fig. 5.13; elasticity constant R against stress. <i>Solid curve</i> : running average filter; sudden increase of noise between strain 0.35 and 0.4 is due to the numerical inverse Laplace solver (Scientist 3.0 by Micromath, Saint Louis, Missouri)	157

Fig. 5.16	Calculation of parameters from Fig. 5.13; viscosity constant η against strain. <i>Solid curve</i> : running average filter; sudden increase of noise between strain 0.35 and 0.4 is due to the numerical inverse Laplace solver (Scientist 3.0 by Micromath, Saint Louis, Missouri).....	158
Fig. 5.17	Calculation of parameters from Fig. 5.13; Difference of correlation coefficients of log fit (r_L) and power fit (r_P), positive difference indicates better fit of power function; <i>solid curve</i> : running average filter; sudden increase of noise between strain 0.35 and 0.4 is due to the numerical inverse Laplace solver (Scientist 3.0 by Micromath, Saint Louis, Missouri).....	159
Fig. 5.18	Determination of R and η ; <i>TP 930</i> (rapid prototyping material), stress relaxation after initial ramp strain at a strain rate of 0.26s^{-1}	160
Fig. 5.19	Determination of R and η ; <i>DM 9750</i> (rapid prototyping material) modulus data obtained at three different strain rates (noisy modulus data were intentionally not filtered)	161
Fig. 5.20	R data of <i>DM 9750</i> (rapid prototyping material); <i>horizontal line</i> : R constant from Fig. 5.19; dots: intercept from sliding window filter with window width 9; <i>bold grey curve</i> : R after applying running average filter of window width 33	161
Fig. 5.21	η data of <i>DM 9750</i> (rapid prototyping material); <i>horizontal line</i> : η constants from Fig. 5.19; <i>dots</i> : gradient from sliding window filter with window width 9; <i>bold grey curve</i> : η after applying running average filter of window width 33	162
Fig. 5.22	Properties of rapid prototyping materials; R against hardness Shore D	163
Fig. 5.23	Properties of rapid prototyping materials; η against hardness Shore D	163
Fig. 5.24	Properties of rapid prototyping materials; η against R	164
Fig. 5.25	Properties of rapid prototyping materials; R/η against hardness Shore D	164
Fig. 5.26	Properties of a cricket ball with five cork layers; (a) R and η against deflection	165
Fig. 5.27	Properties of a cricket ball with five cork layers; stiffness against deflection, the <i>black solid lines</i> show the experimental data, and the <i>gray circles</i> indicate the stiffness recalculated from R , η , deflection and deflection rate with (5.77)	165

Fig. 5.28	Properties of a cricket ball with five cork layers; force against deflection, the <i>black solid lines</i> show the experimental data, the <i>black dashed lines</i> (“1”) indicate the force calculated from (5.79), and the <i>grey dashed lines</i> (“2”) represent the numerical integration of the stiffness recalculated from (5.77)	166
Fig. 6.1	Geometry of the intrinsic beam in the undeformed and deformed configurations	172
Fig. 6.2	Small differential element used to derive a relative position vector in terms of the intrinsic metrics net curvature κ and strain $\mathbf{f}$	174
Fig. 6.3	Comparisons of strain histories predicted by an <i>ABAQUS</i> beam (<i>circular markers</i>) and the intrinsic beam (<i>lines</i>) finite element models for the case of simultaneous twisting and bending loads	183
Fig. 6.4	Comparisons of bending curvature histories predicted by an <i>ABAQUS</i> beam (<i>circular markers</i>) and the intrinsic beam (<i>lines</i>) finite element models for the case of simultaneous twisting and bending loads	184
Fig. 6.5	Comparisons of torsion histories predicted by an <i>ABAQUS</i> beam (a) and the intrinsic beam (b) finite element models for the case of simultaneous twisting and bending loads	185
Fig. 6.6	Geometry of the graphene sheet; representative volume element; final nanotube configuration	186
Fig. 6.7	Snapshots of the dynamic response of a (10, 10) armchair nanotube to a follower end load spaced at intervals of 5×10^3 time units (a) for the loading phase starting at time 0.0 and ending at 8.0×10^4 and (b) the unloading phase starting at time 8.0×10^4 and ending at time 1.5×10^4 . Note that the force is rendered only twice in (a) for illustration purposes, but is present at each snapshot.....	191
Fig. 6.8	Configurations employed in developing the helical spring model. Material points along a straight reference configuration Ω_{ref} are mapped to an initial configuration Ω_0 via initial curvature and strain $\mathbf{K}_0, \boldsymbol{\gamma}_0$. Similar mappings hold for a deformed configuration Ω_f . The latter two configurations are related by mappings which invoke net curvature and strain, $\hat{\mathbf{K}}, \hat{\boldsymbol{\gamma}}$	193
Fig. 6.9	FFT of $\hat{\mathbf{K}}_2$ at node 30 – example fixed–fixed spring discretized using 48 elements (97 nodes)	198
Fig. 6.10	Modal convergence with number of intrinsic finite elements used for first example spring – longitudinal modes	198

Fig. 6.11	Modal convergence with number of intrinsic finite elements used for first example spring – transverse modes	199
Fig. 6.12	FFT of $\hat{K}_2$ at node 30 – example fixed-free spring discretized using 48 elements (97 nodes)	200
Fig. 6.13	Initial spring configurations resulting from application of moderate-magnitude impulsive longitudinal loading. Ensuing motion is on the same order of magnitude as the configurations depicted	201
Fig. 6.14	FFT of $\hat{K}_2$ at node 30 following application of moderate loading – example fixed-free spring discretized using 48 elements (97 nodes)	201
Fig. 6.15	Time histories of curvature $\hat{K}_2$ at node 30 following application of harmonic loading – example fixed-free spring discretized using 48 elements (97 nodes). Two loading cases are depicted: 52.43 Hz, which is a potential secondary resonance, and 60.0 Hz where no resonances are expected	202
Fig. 6.16	Time histories of curvature $\hat{K}_2$ at node 30 following application of harmonic loading – example fixed-free spring discretized using 48 elements (97 nodes). Three loading cases are depicted: 52.43 Hz, 60.0 Hz, and 63.1 Hz	202
Fig. 6.17	Initial spring configurations resulting from application of large-magnitude impulsive transverse loading	203
Fig. 6.18	FFT of $\hat{K}_2$ at node 30 following application of large-amplitude loading	204
Fig. 7.1	Slack mooring system	212
Fig. 7.2	Coordinate system	214
Fig. 7.3	Coordinate transformation	214
Fig. 7.4	Mooring line	215
Fig. 7.5	Model node	215
Fig. 7.6	Mooring line network	216
Fig. 7.7	Rigid body force/torques	218
Fig. 7.8	Segment	219
Fig. 7.9	Extension	219
Fig. 7.10	Unit vectors	220
Fig. 7.11	Redundant line	232
Fig. 7.12	Redundant line equilibrium position	232
Fig. 7.13	Case 1: No stream velocity	233
Fig. 7.14	Case 2: Stream velocity $\bar{v} = [0, Z^{1.4}, 0]^T$	234
Fig. 8.1	Configuration of a deployable mesh reflector	238
Fig. 8.2	3D truss model of mesh reflectors	238
Fig. 8.3	A truss element in undeformed and deformed configurations	244
Fig. 8.4	Nodal displacements and force balance in local coordinate	245

Fig. 8.5	An example of deployable mesh reflector	254
Fig. 8.6	Optimal vertical external loads	255
Fig. 8.7	Optimal original length of members	255
Fig. 8.8	Initial shape of the mesh reflector	256
Fig. 8.9	Actual deformed shape of the mesh reflector	256
Fig. 8.10	Element tensions at the deformed configuration.....	257
Fig. 8.11	1st mode of the mesh reflector: side-wing mode (x direction).....	258
Fig. 8.12	2nd mode of the mesh reflector: side-wing mode (y direction).....	258
Fig. 8.13	3rd mode of the mesh reflector: up-and-down mode	258
Fig. 8.14	4th mode of the mesh reflector: breathing mode	259
Fig. 8.15	Impact of thermal effects on natural frequencies	260
Fig. 8.16	Impact of external load on natural frequencies	260
Fig. 8.17	R & D progress of ASC architecture	261
Fig. 8.18	3D plots of the designate shape for the 835-node model.....	261
Fig. 9.1	General structure of a brake-by-wire system	266
Fig. 9.2	Block diagram of the e-caliper control system in a typical EMB design	267
Fig. 9.3	The diagram of the electromechanical brake caliper. 1 stator field winding, 2 brake pads, 3 ball-screw, 4 planetary gear-set, 5 thrust bearing, 6 clamp force sensor location, 7 resolver location, 8 permanent rotor magnet location, 9 load distribution plate, 10 nut, 11 caliper bridge	268
Fig. 9.4	Arrangement of the strain gauges in each load cell around the load sleeve and Strain gauge electrical circuitry	269
Fig. 9.5	A hysteretic behaviour is observed when the clamp force measurements are plotted versus actuator displacement	270
Fig. 9.6	A picture of the ball-screw and the load sleeve with the key on it	270
Fig. 9.7	Modelling the hysteretic slippage as a parallel combination of saturating elasto-slip elements	272
Fig. 9.8	Stiffness curves of the spring elements in the model of Fig. 9.7	272
Fig. 9.9	Modelling the hysteretic slippage as a parallel combination of saturating elasto-slip elements	273
Fig. 9.10	An example of characteristic curve parameter updating upon the termination of a local hysteresis cycle and start of the next cycle	276
Fig. 9.11	A flowchart for the proposed automatic calibration technique using the hysteresis model (9.5)	277
Fig. 9.12	A picture of the experimental setup	278
Fig. 9.13	Position of the actuator during the experiment	279
Fig. 9.14	Variation of characteristic curve	279

Fig. 9.15	Clamp force measurements by the external and internal sensors during the experiment: The internal sensor measurement has been corrected by calculating and removing its hysteresis part.....	280
Fig. 9.16	Error of the force estimates with respect to their true values	280
Fig. 10.1	Schematic diagram of flow around circular cylinder	284
Fig. 10.2	Schematic diagram of characteristic	286
Fig. 10.3	Wake patterns at low Re number	291
Fig. 10.4	The relation between Re and St (Henderson 1997).....	291
Fig. 10.5	Saddle point (<i>left</i>) and center (<i>right</i>) in two-dimensional incompressible flows (Bisgaard 2005)	293
Fig. 10.6	The cusp bifurcation, a loop is appearing or disappearing in the flow	294
Fig. 10.7	Homoclinic connection of a saddle point (<i>left</i> , structurally stable) and heteroclinic connection (<i>right</i> , structurally unstable).....	294
Fig. 10.8	Streamline topology bifurcation scenarios at $Re = 100$ (Bisgaard 2005)	295
Fig. 10.9	Vortex shedding in a period at $Re = 100$, and the time has been nondimensionalized	296
Fig. 10.10	Vortex shedding in a period at $Re = 100$, and the time has been nondimensionalized	297
Fig. 10.11	Two dimensional steady flow separation.....	298
Fig. 10.12	Movements of unstable manifold in one period ($T = 1$). (a) Flow with slip boundary conditions. (b) Flow with nonslip boundary conditions.....	300
Fig. 10.13	Pressure contour of the mean flow	303
Fig. 10.14	Pressure contour of POD modes	304
Fig. 10.15	Bifurcation diagram of the system with respect to the Reynolds number.....	305
Fig. 10.16	Eigenvalues of the Jacobian matrix for different Reynolds number.....	305
Fig. 10.17	Time history of first mode for different mode number. (a) $Re = 20$, (b) $Re = 100$, (c) $Re = 200$, (d) $Re = 200$ (enlarge)	306
Fig. 10.18	A schematic of the curve of neutral stability	310
Fig. 10.19	Curves of neutral stability for laminar-boundary profiles with different shape factors, after Schlichting and Ulrich (Schlichting and Gersten 2000)	311
Fig. 11.1	A wheel rolling down an inclined plane under gravity	333
Fig. 11.2	A two degree-of-freedom multi-body system	335

Fig. 11.3	Decomposition of the multi-body system shown in Fig. 11.2 using more than two coordinates	337
Fig. 12.1	An element on the middle surface of shell in a relative coordinate system	352
Fig. 12.2	Geometry of truncated conical shell	353
Fig. 12.3	Comparison of nonlinear frequency of simply supported cylindrical shell ($\Omega_1 = 0$, $R/L = 1.0$, $R/h = 25$, $\varphi = 0$, $n = 3$)	361
Fig. 12.4	Effects of angle velocity on nonlinear frequency of simply supported truncated conical shell ($R/L = 1.0$, $R/h = 25$, $\varphi = 30$, $n = 3$)	361
Fig. 12.5	Effects of boundary conditions on nonlinear frequency of truncated conical shell ($\Omega_1 = 1$, $R/L = 0.5$, $R/h = 20$, $\varphi = 30$, $n = 3$)	361
Fig. 12.6	Effect of radius-to-length ratio on nonlinear frequency of clamped truncated conical shell ($\Omega_1 = 1$, $R/h = 20$, $\varphi = 30$, $n = 3$)	362
Fig. 12.7	Effect of semi-vertex angle on nonlinear frequency of simply supported truncated conical shell ($\Omega_1 = 1$, $R/L = 0.5$, $R/h = 20$, $n = 3$)	362
Fig. 12.8	Physical relationship of the truncated conical shallow shell	363
Fig. 12.9	(a) Time history curve. (b) Phase plane curve. (c) Poincare map	367
Fig. 12.10	(a) Time history curve. (b) Phase plane curve. (c) Poincare map	368
Fig. 12.11	(a) Time history curve. (b) Phase plane curve. (c) Poincare map	369
Fig. 12.12	Amplitude frequency response curves of a truncated conical shell	371
Fig. 12.13	Main dynamic area of instability of a truncated conical shell	372
Fig. 12.14	Internal response between the (1,1) modal and (1,3) modal on the transverse direction of the rotary shell	375
Fig. 12.15	Internal response between the (1,1) modal and (1,3) modal on the circle direction of the rotary shell	375
Fig. 12.16	Internal response between the (1,1) modal and (1,3) modal on the longitudinal direction of the rotary shell	376
Fig. 12.17	The amplitude and frequency response curves of the rotary shell corresponding to the (2, 2) modal vibration ($\Omega_1/\Omega_r = 0.4$)	380
Fig. 12.18	The internal resonance characters between the (1, 1) modal and (2, 2) modal of the system as well as the effects of rotary speed to the amplitude and frequency response curves of the rotary shell corresponding to (2, 2) modal vibration ($\Omega_1/\Omega_r = 0.4$)	381

Fig. 12.19	The amplitude and frequency response curves when the shell is oscillating with (1, 1) modal ($f_{22} = 0, a_{12} = 0.3$)	382
Fig. 12.20	The internal response between the modal (1,1) and modal (2, 2) of the shell ($f_{22} = 8, a_{12} = 0.5$).....	384
Fig. 12.21	The effect of the rotary speed Ω_1 on the main dynamic unstable area of the system ($H = 0.1, \lambda_2 = 0.6$)	387
Fig. 12.22	The effects of the thickness of the cylindrical shell H on the main dynamic unstable area of the system ($\Omega_1 = 0.1, \lambda_2 = 0.4$)	387
Fig. 13.1	World (W) and Quadrotor-fixed (Q) frames axes and sign convention. Rotation around the axes of frame Q is expressed using Euler angles. The two frames are related through rotation matrix (${}^W R_Q$) and translation vector (${}^W t_Q$)	395
Fig. 13.2	Model of the quadrotor (top view) showing direction of propeller rotation and reactive torques (τ_i)	397
Fig. 13.3	Model of the quadrotor (side view) for deriving roll and pitch equations of motion	397
Fig. 13.4	(a) Quadrotor with IR reflectors attached to the front, left, and right ends (b) <i>trackable</i> object seen in software and its virtual center defined in the middle	401
Fig. 13.5	A camera mounted at the front of the quadrotor.....	402
Fig. 13.6	Rotation and translation matrices calculated by classicPOSIT relating object frame (O) to camera frame (C).....	403
Fig. 13.7	Target object with dimensions and object frame defined.....	404
Fig. 13.8	Target object feature points extraction – Image processing flowchart	405
Fig. 13.9	Image processing results (a) acquired image (b) segmented LED location (c) LED detected (d) segmented window location (e) corners detected in image (f) detected corners of window before sort (g) five feature points detected after sort and undistortion	406
Fig. 13.10	Hash tables for undistortion of image coordinates (a) Horizontal image coordinate, u (b) Vertical image coordinate, v	407
Fig. 13.11	6DOF pose estimation from detected feature point locations	408
Fig. 13.12	Real-time pose estimation test setup showing all four coordinate frames and OptiTrack cameras	410
Fig. 13.13	Comparison of X -translation estimated by OptiTrack and by classicPOSIT. Each data point is the mean value calculated from 150 samples in each test	412
Fig. 13.14	Comparison of Y -translation estimated by OptiTrack and by classicPOSIT. Each data point is the mean value calculated from 150 samples in each test	412

Fig. 13.15 Comparison of Z-translation estimated by OptiTrack and by classicPOSIT. Each data point is the mean value calculated from 150 samples in each test	413
Fig. 13.16 Comparison of roll angle estimated by OptiTrack and by classicPOSIT. Each data point is the mean value calculated from 150 samples in each test	413
Fig. 13.17 Comparison of pitch angle estimated by OptiTrack and by classicPOSIT. Each data point is the mean value calculated from 150 samples in each test	414
Fig. 13.18 Comparison of yaw angle estimated by OptiTrack and by classicPOSIT. Each data point is the mean value calculated from 150 samples in each test	414
Fig. 13.19 Error of classicPOSIT-based translational estimates compared to OptiTrack-based values	416
Fig. 13.20 Error of classicPOSIT-based rotational estimates compared to OptiTrack-based values	416
Fig. 14.1 Configuration of the entire experimental setup	423
Fig. 14.2 Physical structure of the system	427
Fig. 14.3 Ideal modeling structure	428
Fig. 14.4 Coordinate frames.....	430
Fig. 14.5 The equilibrium manifold	436
Fig. 14.6 Equilibrium input voltage to actuator	436
Fig. 14.7 Locus of transfer function zeros as ϕ is varied from 0° to 90°	442
Fig. 14.8 Overview of system identification.....	444
Fig. 14.9 Physical configuration of balancing mechanism.....	446
Fig. 14.10 Configuration of the entire experimental setup	446
Fig. 14.11 System used for identification	448
Fig. 14.12 Comparison between real and simulation data for $\phi = 20^\circ$ using raw data, Fit = $-1743; 85.03$	452
Fig. 14.13 Comparison between real and simulation data for $\phi = 20^\circ$ using estimated data, Fit = $88.0846; 92.2398$	452
Fig. 14.14 Comparison between real and simulation data for $\phi = 30^\circ$ using raw data, Fit = $-1386; 82.9$	454
Fig. 14.15 Comparison between real and simulation data for $\phi = 30^\circ$ using estimated data, Fit = $87.8; 98.6$	455
Fig. 14.16 Comparison between real and simulation data for $\phi = 40^\circ$ using raw data, Fit = $-97.9; 82.0$	455
Fig. 14.17 Comparison between real and simulation data for $\phi = 40^\circ$ using estimated data, Fit = $83.3; 99.1$	456
Fig. 14.18 Comparison between real and simulation data for $\phi = 50^\circ$ using raw data, Fit = $-561.6; 80.5$	456

Fig. 14.19	Comparison between real and simulation data for $\phi = 50^\circ$ using estimated data, Fit = 82.2;97.8	457
Fig. 14.20	Comparison between real and simulation data for $\phi = 60^\circ$ using raw data, Fit = -344.4; 76.7	457
Fig. 14.21	Comparison between real and simulation data for $\phi = 60^\circ$ using estimated data, Fit = 83.3;98.0	458
Fig. 14.22	Pole-Zero locus using estimated parameters	458
Fig. 14.23	Simulation response of FL vs. LQR control in response to constant disturbance	467
Fig. 14.24	Simulation result of FL vs. LQR control in response to a sinusoidal disturbance	468
Fig. 14.25	Simulation result of FL vs. LQR in response to two pulses	469
Fig. 14.26	Simulation result of FL vs. LQR control in response to nonzero initial conditions	470
Fig. 14.27	Simulation result of FL vs. LQR control in response to nonzero initial conditions	470
Fig. 14.28	Simulation result of FL vs. LQR control in response to nonzero initial conditions	471
Fig. 14.29	Experimental result of FL control in response to two pulses	472
Fig. 15.1	The schematic drawing of the passive and active mechanisms responsible for stabilizing the HNC. The passive part (single-inverted pendulum model with inertia and viscoelastic elements) is considered as a physical model in this study	477
Fig. 15.2	Experiment design for measuring the dynamics of Head-Neck	478
Fig. 15.3	(a) A double-degree-of-freedom model of the HNC with its schematic draw. (b) The angular displacements, θ_1 and θ_2 , of the model	481
Fig. 15.4	The mean values of the coherency functions for four subjects. Each graph belongs to one subject	488
Fig. 15.5	Comparison of the experimental (Exp.) and simulated (Sim.) results of the magnitudes of the transfer functions for four subjects. Note that the # sign indicates the subject number	489
Fig. 15.6	Comparison of the experimental (Exp.) and simulated (Sim.) results of the phases of the transfer functions for four subjects. Note that the # sign indicates the subject number ...	490
Fig. 15.7	Comparison of the experimental (Exp.) and simulated (Sim.) outputs (<i>lower panel</i>) for one subject in the time domain when the input (<i>the upper panel</i>) is a Guassian random vibration (validation of the model)	491
Fig. 15.8	HNC passive and active elements	495

Fig. 15.9	The schematic drawing of the experiment design	496
Fig. 15.10	A random phase multisine excitation signal	498
Fig. 15.11	The power spectrum of the multisine input signal.....	499
Fig. 15.12	The block diagram of the HNC in the AV and AN conditions.....	511
Fig. 15.13	The magnitudes of the HNC transfer function in three conditions of P, AV, and AN	514
Fig. 15.14	The phases of the HNC transfer function in three conditions of P, AV, and AN	515
Fig. 15.15	Comparison of the experimental (Exp.) and simulated (Sim.) results of the magnitudes of the HNC transfer functions, corresponding to the nine subjects, in the P condition...	516
Fig. 15.16	Comparison of the experimental (Exp.) and simulated (Sim.) results of the phases of the HNC transfer functions, corresponding to the nine subjects, in the P condition...	517
Fig. 15.17	Comparison of the experimental (Exp.) and simulated (Sim.) results of the magnitudes of the HNC transfer functions, corresponding to the nine subjects, in the AV condition	518
Fig. 15.18	Comparison of the experimental (Exp.) and simulated (Sim.) results of the phases of the HNC transfer functions, corresponding to the nine subjects, in the AV condition	519
Fig. 15.19	Comparison of the experimental (Exp.) and simulated (Sim.) results of the magnitudes of the HNC transfer functions, corresponding to the nine subjects, in the AN condition	520
Fig. 15.20	Comparison of the experimental (Exp.) and simulated (Sim.) results of the phases of the HNC transfer functions, corresponding to the nine subjects, in the AN condition	521