Springer Complexity

Springer Complexity is an interdisciplinary program publishing the best research and academic-level teaching on both fundamental and applied aspects of complex systems-cutting across all traditional disciplines of the natural and life sciences, engineering, economics, medicine, neuroscience, social and computer science.

Complex Systems are systems that comprise many interacting parts with the ability to generate a new quality of macroscopic collective behavior the manifestations of which are the spontaneous formation of distinctive temporal, spatial or functional structures. Models of such systems can be successfully mapped onto quite diverse "real-life" situations like the climate, the coherent emission of light from lasers, chemical reaction-diffusion systems, biological cellular networks, the dynamics of stock markets and of the internet, earthquake statistics and prediction, freeway traffic, the human brain, or the formation of opinions in social systems, to name just some of the popular applications.

Although their scope and methodologies overlap somewhat, one can distinguish the following main concepts and tools: self-organization, nonlinear dynamics, synergetics, turbulence, dynamical systems, catastrophes, instabilities, stochastic processes, chaos, graphs and networks, cellular automata, adaptive systems, genetic algorithms and computational intelligence.

The three major book publication platforms of the Springer Complexity program are the monograph series "Understanding Complex Systems" focusing on the various applications of complexity, the "Springer Series in Synergetics", which is devoted to the quantitative theoretical and methodological foundations, and the "Springer Briefs in Complexity" which are concise and topical working reports, case-studies, surveys, essays and lecture notes of relevance to the field. In addition to the books in these two core series, the program also incorporates individual titles ranging from textbooks to major reference works.

Editorial and Programme Advisory Board

Understanding Complex Systems

Founding Editor: S. Kelso

Future scientific and technological developments in many fields will necessarily depend upon coming to grips with complex systems. Such systems are complex in both their composition – typically many different kinds of components interacting simultaneously and nonlinearly with each other and their environments on multiple levels – and in the rich diversity of behavior of which they are capable.

The Springer Series in Understanding Complex Systems series (UCS) promotes new strategies and paradigms for understanding and realizing applications of complex systems research in a wide variety of fields and endeavors. UCS is explicitly transdisciplinary. It has three main goals: First, to elaborate the concepts, methods and tools of complex systems at all levels of description and in all scientific fields, especially newly emerging areas within the life, social, behavioral, economic, neuro- and cognitive sciences (and derivatives thereof); second, to encourage novel applications of these ideas in various fields of engineering and computation such as robotics, nano-technology and informatics; third, to provide a single forum within which commonalities and differences in the workings of complex systems may be discerned, hence leading to deeper insight and understanding.

UCS will publish monographs, lecture notes and selected edited contributions aimed at communicating new findings to a large multidisciplinary audience.

More information about this series at http://www.springer.com/series/5394

Xingjian Jing • Ziqiang Lang

Frequency Domain Analysis and Design of Nonlinear Systems based on Volterra Series Expansion

A Parametric Characteristic Approach

Springer

Xingjian Jing
The Hong Kong Polytechnic University
Hong Kong
PR China

Ziqiang Lang
The University of Sheffield
Sheffield
UK

ISSN 1860-0832
ISSN 1860-0840 (electronic)
ISBN 978-3-319-12390-5
ISBN 978-3-319-12391-2 (eBook)
DOI 10.1007/978-3-319-12391-2
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2015931644

Printed on acid-free paper

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

To the authors' families.

Preface

Nonlinearities are ubiquitous and often incur twofold influence, which could be a source of troubles bringing uncertainty, inaccuracy, instability or even disaster in practice, and might also be a superior and beneficial factor for system performance improvement, energy cost reduction, safety maintenance or health monitoring, etc. Therefore, analysis and design of nonlinear systems are important and inevitable issues in both theoretical study and practical applications.

Several methods are available in the literature to this aim including perturbation method, averaging method and harmonic balance method, etc. Nonlinear analysis can also be conducted in the frequency domain based on the Volterra series theory. The latter is a very useful tool with some special and beneficial features to tackle nonlinear problems. It is known that there is a considerably large class of nonlinear systems which allow a Volterra series expansion. Based on the Volterra series, the generalized frequency response function (GFRF) was defined as a multi-variate Fourier transform of the Volterra kernels in the 1950s. This presents a fundamental basis and therefore initiates a totally new theory or area for nonlinear analysis and design in the frequency domain.

The frequency-domain nonlinear analysis theory and methods, based on the Volterra series approach, are observed with a faster development starting from the late 1980s or the early 1990s. Recursive algorithms for computation of the GFRFs for a given parametric nonlinear autoregressive with exogenous input (NARX) model or a given nonlinear differential equation (NDE) model are developed, and output frequency response of nonlinear systems and it properties are investigated accordingly. The area is becoming even more active in recent years. Much more efforts and progress can be seen in the development of application-oriented theory and methods based on the GFRF concept. These include the concepts of nonlinear output spectrum (or output frequency response function) and nonlinear output frequency response function, parametric characteristic analysis, energy transfer properties and various applications in vibration control by exploring nonlinear benefits, fault detection, modelling and identification, data analysis and interpretation, etc.

This book is a systematic summary of some new advances in this area mainly done by the authors in the past years starting from when the first author pursued his Ph.D. degree in the University of Sheffield in 2005. The main results are tried to be formulated uniformly with a parametric characteristic approach, which provides a convenient and novel insight into the nonlinear influence on system output response in terms of characteristic parameters and thus can facilitate nonlinear analysis and design in the frequency domain. The book starts with a brief introduction to the background of nonlinear analysis in the frequency domain, followed by the recursive algorithms for computation of GFRFs for different parametric models, and nonlinear output frequency properties. Thereafter the parametric characteristic analysis method is introduced, which leads to new understanding and formulation of the GFRFs, new concepts about nonlinear output spectrum and new methods for nonlinear analysis and design, etc. Based on the parametric characteristic approach, nonlinear influence in the frequency domain can be investigated with a novel insight, i.e. alternating series, which is followed by some application results in vibration control. Magnitude bounds of frequency response functions of nonlinear systems can also be studied with a parametric characteristic approach, which results in novel parametric convergence criteria for any given parametric nonlinear model whose input–output relationship allows a convergent Volterra series expansion. Although very important and fundamental, these results are summarized at the end of this book.

This book targets those readers (especially Ph.D. students and research staff) who are working in the areas related to nonlinear analysis and design, nonlinear signal processing, nonlinear system identification, nonlinear vibration control and so on. It particularly serves as a good reference for those who are studying frequency-domain methods for nonlinear systems.

Hong Kong, P.R. China Xingjian Jing
June 2014

Acknowledgements

The first author would like to give his thanks to the Department of Mechanical Engineering, the Hong Kong Polytechnic University, for support in research and to his Ph.D. students for their dedicated efforts in the research group.

The authors are also indebted to all current and/or previous colleagues, most importantly to those in the University of Sheffield (UK) for extensive discussions, invaluable suggestions and generous supports.

The authors wish to acknowledge the support from the Hong Kong GRF project RGC Ref No. 15206514, the China NSFC project No. 61374041 and the UK EPSRC project EP/F017715/1.

Finally, the authors would like to give the greatest gratitude with heart and soul to their families, respectively, for everlasting and abundant understanding and support.

XJ Jing
ZQ Lang

Contents