

G. Radons, R. Neugebauer (Eds.)

Nonlinear Dynamics of Production Systems

With a Foreword by Hans-Peter Wiendahl



WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

G. Radons, R. Neugebauer (Eds.)
**Nonlinear Dynamics of Production
Systems**

G. Radons, R. Neugebauer (Eds.)

Nonlinear Dynamics of Production Systems

With a Foreword by Hans-Peter Wiendahl



WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

Editors

Prof. Dr. Günter Radons
Technische Universität Chemnitz
Institut für Physik, Theoretische Physik I
Komplexe Systeme und Nichtlineare Dynamik

Prof. Dr.-Ing. Reimund Neugebauer
Fraunhofer Institut für Werkzeugmaschinen
und Umformtechnik IWU Chemnitz

Cover picture

The photograph shows a working finger milling tool with spiral chips formed. The state space trajectories of the insert visualize the nonlinear dynamics of regenerative chatter which may perturb such machining operations. Courtesy: Gabor Stépán, Budapest.

This book was carefully produced. Nevertheless, editors, authors, and publisher do not warrant the information contained therein to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for British Library Cataloging-in-Publication Data:

A catalogue record for this book is available from the British Library

Bibliographic information published by Die Deutsche Bibliothek.

Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at <<http://dnb.ddb.de>>.

© 2004 WILEY-VCH Verlag GmbH & Co.
KGaA, Weinheim

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – nor transmitted or translated into machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Printed in the Federal Republic of Germany
Printed on acid-free paper

Composition Steingraeber Satztechnik GmbH,
Dossenheim
Printing Druckhaus Darmstadt GmbH, Darmstadt
Bookbinding Großbuchbinderei J. Schäffer
GmbH & Co. KG., Grünstadt

ISBN 3-527-40430-9

Foreword

Since the 1980s both a distinct acceleration and an increasing interlinkage of technical and logistic manufacturing processes can be observed worldwide. This has led to phenomena which are often graphically described as “turbulent”. Conventional linear models and approaches obviously no longer suffice to control the corresponding sudden and apparently unforeseeable process changes.

Prompted by works on chaos research in the mathematics and physics, a group of colleagues at the German Academic Society for Production Engineering (Wissenschaftliche Gesellschaft für Produktionstechnik WGP) posed the question whether the theories propounded by “chaos researchers” to describe non-linear dynamic systems might not also contribute to a deeper understanding of the behaviour of high-precision manufacturing processes, complex production facilities and cross-linked logistic processes.

To assess the need for action, a workshop on “Potentials of chaos research in manufacturing sciences” sponsored by the Volkswagen Foundation was staged in Hanover in 1994. About 30 participants from the manufacturing sciences, natural sciences and industry took part. The evaluation of this workshop and contacts with other scientists led to a joint proposal by Professors Wiendahl (Hanover), Weck (Aachen) and Lierath (Magdeburg) to initiate research with focus on the “Investigation of non-linear dynamic effects in production technology systems”.

In the summer of 1995, the board of trustees of the Volkswagen Foundation agreed to set up this research program, which came to a conclusion at the end of 2001. The Foundation funded a total of 33 joint projects with up to six research groups involved. An important condition for the funding of a project was the collaboration of physicists and/or mathematicians with engineers. The Foundation granted a total sum of 13 mill. Euro for projects with this research focus, with 7.6 mill. Euro to go to the engineering sciences, 3.9 mill. Euro to physics and 1.5 mill. Euro to mathematics. In April 2003, the fourth and final symposium took place in Chemnitz.

This book contains selected and edited contributions to this symposium. The spectrum of the topics dealt with ranges from the modelling and optimisation of classical manufacturing processes, such as cutting, milling or grinding, to the development of innovative control processes for complex manufacturing machines and logistic analysis and modelling of production technology systems. These can now be better understood as regards their structure and dynamics, in particular their irregular behaviour and their characteristic complexity. Building on this, new concepts for their planning, design and control were designed.

In retrospect, it is clear that the initiative succeeded not only in gaining important scientific insights within the projects and on workshops, but also in promoting and strengthening the ongoing co-operation between engineers, physicists and mathematicians in this new field of manufacturing science.

The initiators and researchers involved would like to thank the Volkswagen Foundation for its generous funding of the projects, symposia and the publication of this book, and are also indebted to Dr Claudia Nitsch and Dr Franz Dettenwanger for their competent and helpful support.

Hans-Peter Wiendahl

Hannover, August 2003

Preface

After more than two decades of intense fundamental research in nonlinear dynamics, time has come to reap the fruits of this field. Applications in the area of production systems are possibly the most important and challenging ones. To enable progress in applying nonlinear dynamics to production systems, one needs the input from theoreticians, who are often affiliated with physics or mathematics departments, and from experts in the engineering sciences. Only a close cooperation between these groups can solve the many problems that arise from the ubiquitous presence of nonlinearities inherent in production processes and manufacturing techniques. This has been recognized clearly almost ten years ago by the initiators of the priority area “Investigations of Non-Linear Dynamic Effects in Production Systems” and the responsible persons at VolkswagenStiftung, the funding organization of this project.

Due to these efforts we are now in the lucky position to report on the progress and the many facets of this new research field. On occasion of the fourth and final symposium of this priority area held on 8–9 April 2003 in Chemnitz, Germany, we asked the members of the priority area and internationally renowned experts in the field to contribute to a book on “Nonlinear Dynamics of Production Systems”. The response was overwhelming and enthusiastic and resulted in the current volume. This is the first book covering nonlinear dynamic effects in the broad field of production systems in such a comprehensive way. Of course, not every problem arising in one of the many different manufacturing techniques or production processes can be solved with the aid of nonlinear dynamics. And of the many cases where the inherent complexity and nonlinearity calls for such methods, we can only present a prototypical selection.

The content of this book is divided into five parts corresponding to different aspects or sub-fields of production systems. Part I is devoted to the dynamics and the optimal organization of whole production lines and general production systems. Classically, such problems have been topics in operations research. Recently, however, with the need for more flexibility and stability of production processes, the central importance of nonlinear dynamic effects has been recognized. Thereby a new field is emerging and the chapters in this part give an overview over these approaches. The aspects that arise are of interest for both the scientist who seeks interesting fields of research and the manager who wants to optimize his workshop. The largest section, Part II, is concerned with various mechanical manufacturing techniques. It reports on recent advances for the long-standing problem of machine chatter appearing in turning, milling, grinding and other mechanical machining operations, but also on new forming techniques. In addition, it treats various other important methods used nowadays to improve quality and performance of these techniques, such as the coating of tools. In a way this and the next part may be regarded as an update and an extension of the previously published Wiley book on “Dynamics and Chaos in Manufacturing Processes”, edited by Francis C. Moon in 1998. Part III deals with certain aspects of the dynamics of machines and robots, which are relevant for or closely related to manufacturing processes. These range from nonlinear vibrations in forming machines and drives to the control of mechanical coordination tasks and the experimental identification of the friction dynamics in mechanical systems. This part also contains an obituary for one of our authors, František Peterka, who died unexpectedly while we were editing this book. In Part IV, non-conventional manufacturing methods, such as water-jet or laser-jet cutting and laser welding are treated. In many respects these advanced techniques complement the more traditional mechanical processes. It turns out, however, that the nonlinear

dynamic phenomenon of pattern formation causes some problems in otherwise advantageous operating regimes. Possible solutions or at least new insights into these problems are provided. Pattern formation also plays a central role for many industrial chemical and electro-chemical processes which are treated in Part V. Often these processes are too complex to be understood in detail, but nevertheless the appearance and identification of certain patterns often helps to determine and control the state of the system, be it in a coal burner, or in an etching process or in a lead battery. This part also reveals that bifurcation and catastrophe theory are valuable tools in designing and controlling chemical processes.

In our opinion the contributions in this book demonstrate very convincingly the ubiquity of nonlinear dynamic effects in almost all aspects of production systems. As a consequence the understanding of such effects becomes an increasingly important pre-requisite for the further development of production techniques and systems. For the nonlinear-dynamics scientist this implies a continuing challenge from interesting real-world problems, and to the engineer it shows that nonlinear dynamics can provide promising approaches for the solution of his problems.

We want to thank all persons who made the publication of this book possible. First we thank the authors who cooperated so constructively and reliably also in our cross-refereeing procedure. Next, also in the name of all authors, we wish to express our gratitude towards the VolkswagenStiftung, Hannover, which funded not only much of the research presented here, but also the symposium in Chemnitz and previous ones from which this book emanated, and which in addition made it possible for this book to appear in color printing. Finally we thank Vera Palmer and Ulrike Werner from Wiley-VCH for their smooth and engaged cooperation, which made the editing of this volume a pleasant endeavor.

Günter Radons

Reimund Neugebauer

Chemnitz, September 2003



Participants of the "4th International Symposium on Investigations of Nonlinear Dynamic Effects in Production Systems" in Chemnitz, 8–9 April 2003

List of Contributors

Farid Al-Bender

Catholic University of Leuven
Department of Mechanical Engineering
farid.al-bender@mech.kuleuven.ac.be

Dieter Armbruster

Arizona State University
Department of Mathematics
dieter@source.la.asu.edu

Ralph T. Bailey

Babcock & Wilcox Canada, Ltd.
RTBailey@babcock.com

Michael Baune

Universität Bremen
Institut für Angewandte und Physikalische
Chemie
m.baune@uni-bremen.de

Andreas Baus

Rheinisch-Westfälische Technische Hochschule
Aachen
Werkzeugmaschinenlabor
a.baus@wzl.rwth-aachen.de

Arno Behrens

Universität der Bundeswehr Hamburg
Laboratorium Fertigungstechnik
Arno.behrens@unibw-hamburg.de

Andrzej Bodnar

Technical University of Szczecin

Ekkard Brinksmeier

Universität Bremen
Labor für Mikroerspannung
brinksme@iwt.uni-bremen.de

Magnus Buhlert

Universität Bremen
Institut für Angewandte und Physikalische
Chemie
buhlert@uni-bremen.de

Leonid A. Bunimovich

Georgia Institute of Technology
School of Mathematics
bunimovh@math.gatech.edu

Adrienn Cser

Universität Erlangen-Nürnberg
Lehrstuhl für Fertigungstechnologie
A.Cser@lft.uni-erlangen.de

C. Stuart Daw

Oak Ridge National Laboratory
Fuels, Engines and Emissions Research Center
dawcs@ornl.gov

Berend Denkena

Universität Hannover
Institut für Fertigungstechnik und
Werkzeugmaschinen
denkena@ifw.uni-hannover.de

S. Diaz Alfonso

Instituto Superiore Politecnico, Havana
Facultad de Ingenieria Chimiza

Thomas Ditzinger

Springer-Verlag, Heidelberg
Ditzinger@Springer.de

Reik Donner

Universität Potsdam
Institut für Physik
reik@agnld.uni-potsdam.de

David Engster

Universität Göttingen
III. Physikalisches Institut
D.Engster@DPI.Physik.Uni-Goettingen.de

Ronald Faassen

Technical University of Eindhoven
Department of Mechanical Engineering
r.p.h.faassen@tue.nl

Spilios D. Fassois

University of Patras
Department of Mechanical and Aeronautical
Engineering
fassois@mech.upatras.gr

Ulrike Feudel

Carl von Ossietzky Universität Oldenburg
 Institut für Chemie und Biologie des Meeres
 U.Feudel@icbm.de

Charles E.A. Finney

Oak Ridge National Laboratory
 Fuels, Engines and Emissions Research Center
 finneyc@ornl.gov

Gerhard Finstermann

Johannes Kepler Universität Linz
 gerhard.finstermann@vai.at

Thomas J. Flynn

Babcock & Wilcox Canada, Ltd.
 TJFlynn@babcock.com

Michael Freitag

Universität Bremen
 Planung und Steuerung produktionstechnischer
 Systeme
 fmt@biba.uni-bremen.de

Rudolf Friedrich

Westfälische Wilhelms-Universität Münster
 Institut für Theoretische Physik
 fiddir@uni-muenster.de

Michael I. Friswell

University of Bristol
 Department of Aerospace Engineering
 m.i.friswell@bristol.ac.uk

Timothy A. Fuller

Babcock & Wilcox Canada, Ltd.
 tafuller@babcock.com

Manfred Geiger

Universität Erlangen-Nürnberg
 Lehrstuhl für Fertigungstechnologie
 m.geiger@lft.uni-erlangen.de

Mark Geisel

Universität Erlangen-Nürnberg
 Lehrstuhl für Fertigungstechnologie
 m.geisel@lft.uni-erlangen.de

Carmen Gerlach

Universität Bremen
 Institut für Angewandte und Physikalische
 Chemie
 cgerlach@uni-bremen.de

Roland Göbel

Universität Dortmund
 Lehrstuhl für Umformtechnik
 Goebel@lfu.mb.uni-dortmund.de

Edvard Govekar

University of Ljubljana
 Faculty of Mechanical Engineering
 edvard.govekar@fs.uni-lj.si

Igor Grabec

University of Ljubljana
 Faculty of Mechanical Engineering
 igor.grabec@fs.uni-lj.si

Janez Gradisek

University of Ljubljana
 Faculty of Mechanical Engineering
 janez.gradisek@fs.uni-lj.si

Karol Grudzinski

Technical University of Szczecin
 konrad@safona.tuniv.szczecin.pl

Maria Haase

Universität Stuttgart
 Institut für Computeranwendungen
 ica2mh@csv.ica.uni-stuttgart.de

Juergen Hahn

Texas A&M University, College Station
 Department of Chemical Engineering
 hahn@tamu.edu

Ernst-Christoph Haß

MIR-Chem GmbH, Bremen
 Hass@mir-chem.de

Bodo Heimann

Universität Hannover
 Institut für Mechanik
 heimann@ifm.uni-hannover.de

Dirk Helbing

Technische Universität Dresden
 Institut für Wirtschaft und Verkehr
 helbing@traffforum.de

Burkhard Heller

Universität Dortmund
Lehrstuhl für Umformtechnik
heller@lfu.mb.uni-dortmund.de

Axel Henning

Fraunhofer Institut für Produktionstechnik
und Automatisierung, Stuttgart
henning@ipa.fhg.de

Helmut J. Holl

Johannes Kepler Universität Linz
Abteilung für Technische Mechanik
helmut.holl@jku.at

Alexander Hornstein

Universität Göttingen
III. Physikalisches Institut
A.Hornstein@DPI.Physik.Uni-Goettingen.de

Tamas Inesperger

Budapest University of Technology and
Economics
Department of Applied Mechanics
inspi@mm.bme.hu

Hans Irschik

Johannes Kepler Universität Linz
Abteilung für Technische Mechanik
Hans.irschik@jku.at

Jörn Jacobsen

Universität Hannover
Institut für Fertigungstechnik und
Werkzeugmaschinen
jacobsen@ifw.uni-hannover.de

Karsten Kalisch

Universität der Bundeswehr Hamburg
Laboratorium Fertigungstechnik
Karsten.kalisch@unibw-hamburg.de

Tamás Kalmár-Nagy

United Technologies Research Center
kalmart@utrc.utc.com

Holger Kantz

Max-Planck-Institut für Physik komplexer
Systeme, Dresden
kantz@mpipks-dresden.mpg.de

Ines Katzorke

Universität Potsdam
Institut für Physik
ines@agnld.uni-potsdam.de

Matthias Kleiner

Universität Dortmund
Lehrstuhl für Umformtechnik
mkleiner@lfu.mb.uni-dortmund.de

Christian Klimmek

Universität Dortmund
Lehrstuhl für Umformtechnik
klimmek@lfu.mb.uni-dortmund.de

Fritz Klocke

Rheinisch-Westfälische Technische Hochschule
Aachen
Werkzeugmaschinenlabor
f.klocke@wzl.rwth-aachen.de

Jan Konvicka

Mikron Comp-Tec AG
jan.konvicka@mikron-ac.com

Vadim Kostrykin

Fraunhofer Institut für Lasertechnik, Aachen
Vadim.kostrykin@ilt.fraunhofer.de

Alexei Kouzmitchev

Westfälische Wilhelms-Universität Münster
Institut für Theoretische Physik
kuz@uni-muenster.de

Jürgen Kurths

Universität Potsdam
Institut für Physik
Jkurths@agnld.uni-potsdam.de

Vincent Lampaert

Catholic University of Leuven
Department of Mechanical Engineering
Vincent.Lampaert@mech.kuleuven.ac.be

Erjen Lefeber

Technical University of Eindhoven
Department of Mechanical Engineering
a.a.j.lefeber@tue.nl

Regina Leopold

Fraunhofer Institut für Werkzeugmaschinen
und Umformtechnik, Chemnitz
leopold@iwu.fhg.de

Jianhui Li

Universität Bremen
Labor für Mikrozerspannung
jli@lfm.uni-bremen.de

Grzegorz Litak

Technical University of Lublin
Department of Applied Physics
litak@archimedes.pol.lublin.pl

Wolfgang Marquardt

Rheinisch-Westfälische Technische Hochschule
Aachen
Lehrstuhl für Prozesstechnik
marquardt@lfpt.rwth-aachen.de

Hendrik Mathes

Universität Bremen
Institut für Angewandte und Physikalische
Chemie
Hendrik@uni-bremen.de

Karl Mayrhofer

Johannes Kepler Universität Linz
Institut für Anwendungsorientierte
Wissensverarbeitung
karl.mayrhofer@vai.at

Jan Michel

Fraunhofer Institut für Lasertechnik, Aachen
Jan.michel@ilt.fraunhofer.de

Martin Mönnigmann

Rheinisch-Westfälische Technische Hochschule
Aachen
Lehrstuhl für Prozesstechnik
moennigmann@lpt.rwth-aachen.de

Francis C. Moon

Cornell University, Ithaca
Sibley School of Mechanical and Aerospace
Engineering
Fcm3@cornell.edu

Alejandro Mora

Universität Stuttgart
Institut für Computeranwendungen
ica2am@csv.uni-stuttgart.de

Steffen Nestmann

Fraunhofer Institut für Werkzeugmaschinen
und Umformtechnik, Chemnitz
Steffen.nestmann@iwu.fraunhofer.de

Reimund Neugebauer

Fraunhofer Institut für Werkzeugmaschinen
und Umformtechnik, Chemnitz
Neugebauer@iwu.fhg.de

Markus Nießen

Fraunhofer Institut für Lasertechnik, Aachen
Markus.niessen@ilt.fraunhofer.de

Henk Nijmeijer

Technical University of Eindhoven
Department of Mechanical Engineering
h.nijmeijer@tue.nl

J.A.J. Oosterling

TNO Institute of Industrial Technology Enschede
Manufacturing Development

Andreas Otto

Universität Erlangen-Nürnberg
Lehrstuhl für Fertigungstechnologie
A.Otto@ift.uni-erlangen.de

Ulrich Parlitz

Universität Göttingen
III. Physikalisches Institut
U.Parlitz@DPI.Physik.Uni-Goettingen.DE

Frantisek Peterka †

Academy of Sciences of the Czech Republic,
Prague
Institute of Thermomechanics

Karsten Peters

Universität Göttingen
III. Physikalisches Institut
karsten@physik3.gwdg.de

Stefan Pfeiffer

Rheinisch-Westfälische Technische Hochschule
Aachen
Lehrstuhl für Lasertechnik

Arkady Pikovsky
 Universität Potsdam
 Institut für Physik
 pikovsky@stat.physik.uni-potsdam.de

Peter Jörg Plath
 Universität Bremen
 Institut für Angewandte und Physikalische
 Chemie
 plath@uni-bremen.de

Thomas Rabbow
 Universität Bremen
 Institut für Angewandte und Physikalische
 Chemie
 rabbow@uni-bremen.de

Günter Radons
 Technische Universität Chemnitz
 Institut für Physik
 Radons@physik.tu-chemnitz.de

Volker Reitmann
 Max-Planck-Institut für Physik komplexer
 Systeme, Dresden
 reitmann@rcs.urz.tu-dresden.de

Rüdiger Rentsch
 Universität Bremen
 Labor für Mikroerspannung
 rentsch@lfm.uni-bremen.de

Dimitris C. Rizos
 University of Patras
 Department of Mechanical and Aeronautical
 Engineering
 Driz@mech.upatras.gr

Alejandro Rodriguez-Angeles
 Technical University of Eindhoven
 Department of Mechanical Engineering
 a.rodriquez@tue.nl

Rafal Rusinek
 Technical University of Lublin
 Department of Applied Mechanics
 raf@archimedes.pol.lublin.pl

Gerhard Schmidt
 Fraunhofer Institut für Werkzeugmaschinen
 und Umformtechnik, Chemnitz
 Schmidt@iwu.fhg.de

Alf Schmieder
 Universität Bremen
 Planung und Steuerung produktionstechnischer
 Systeme
 smi@biba.uni-bremen.de

Bernd Scholz-Reiter
 Universität Bremen
 Planung und Steuerung produktionstechnischer
 Systeme
 bsr@biba.uni-bremen.de

Wolfgang Schulz
 Fraunhofer Institut für Lasertechnik, Aachen
 Wolfgang.schulz@ilt.fraunhofer.de

Oliver Schütte
 Universität Hannover
 Institut für Mechanik
 schuette@ifm.uni-hannover.de

Udo Schwarz
 Universität Potsdam
 Institut für Physik
 USchwarz@Agnld.uni-potsdam.de

Gabor Stepan
 Budapest University of Technology and
 Economics
 Department of Applied Mechanics
 stepan@mm.bme.hu

Uwe Sydow
 MIR-Chem GmbH, Bremen
 sydow@mir-chem.de

Kazimierz Szabelski
 Technical University of Lublin
 Department of Applied Mechanics
 mechstos@archimedes.pol.lublin.pl

Robert Szalai
 Budapest University of Technology and
 Economics
 Department of Applied Mechanics
 szalai@mm.bme.hu

Palaniappagounder Thangavel
 Universität Bremen
 Institut für Angewandte und Physikalische
 Chemie
 Thangavelp@yahoo.com

Hans Kurt Tönshoff
 Universität Hannover
 Institut für Fertigungstechnik und
 Werkzeugmaschinen
 toenshoff@ifw.uni-hannover.de

Ubbo Visser
 Universität Bremen
 Technologie-Zentrum Informatik
 Visser@tzi.de

Nathan van de Wouw
 Technical University of Eindhoven
 Department of Mechanical Engineering
 n.v.d.wouw@tue.nl

E. van Raaij
 MIR-Chem GmbH, Bremen
 info@mir-chem.de

Jerzy Warminski
 Technical University of Lublin
 Department of Applied Mechanics
 jwar@archimedes.pol.lublin.pl

Frank Weidermann
 Fachhochschule Mittweida
 Fachbereich Maschinenbau/Feinwerktechnik
 Frank.weidermann@htwm.de

A. Wessel
 Universität Potsdam
 Institut für Physik

Niels Wessel
 Universität Potsdam
 Institut für Physik
 niels@agnld.uni-potsdam.de

Bert Westhoff
 Universität der Bundeswehr Hamburg
 Laboratorium Fertigungstechnik
 Bert.westhoff@unibw-hamburg.de

Engelbert Westkämper
 Fraunhofer Institut für Arbeitswirtschaft
 und Organisation, Stuttgart
 wke@ipa.fhg.de

Hans-Peter Wiendahl
 Universität Hannover
 Institut für Fabrikanlagen und Logistik
 wiendahl@ifa.uni-hannover.de

Jochen Worbs
 Universität Hannover
 Institut für Fabrikanlagen und Logistik
 worbs@ifa.uni-hannover.de

Keith Worden
 University of Sheffield
 Department of Mechanical Engineering
 K.Worden@sheffield.ac.uk

Jens Wulfsberg
 Universität der Bundeswehr Hamburg
 Laboratorium Fertigungstechnik
 Jens.wulfsberg@unibw-hamburg.de

Contents

| | | |
|----------|---------------------------------------------------------------------------------------------------|-----------|
| I | Dynamics and Control of Production Processes | 1 |
| 1 | Dynamical Systems and Production Systems | 5 |
| 1.1 | Introduction | 5 |
| 1.2 | The Bucket Brigade Production System | 5 |
| 1.2.1 | Re-ordering | 7 |
| 1.2.2 | Non-constant Speeds | 8 |
| 1.2.3 | Bucket Brigades and Learning | 11 |
| 1.3 | Fluid Models of Production Networks | 12 |
| 1.4 | Dynamics of Supply Chains | 17 |
| 1.4.1 | Simulation and Control | 21 |
| | Bibliography | 22 |
| 2 | Method of Stabilization of a Target Regime in Manufacturing and Logistics | 25 |
| 2.1 | Introduction | 25 |
| 2.1.1 | Stabilization of a Target Regime (STR Method) | 26 |
| 2.1.2 | Constraints-based Hierarchy of Models | 27 |
| 2.1.3 | The Algorithm of the Optimal Management of the Systems in Work-sharing Manufacturing | 27 |
| 2.2 | The Hierarchy of Models | 28 |
| 2.3 | Dynamics of the Models in the Hierarchy | 31 |
| 2.4 | Algorithm of Stabilization of the Target Regime for OWS Models | 35 |
| 2.5 | Concluding Remarks | 36 |
| | Bibliography | 37 |
| 3 | Manufacturing Systems with Restricted Buffer Sizes | 39 |
| 3.1 | Introduction | 39 |
| 3.2 | Hybrid Models | 40 |
| 3.2.1 | Switched Arrival and Server Systems | 41 |
| 3.2.2 | Limiting Cases | 43 |
| 3.2.3 | Dynamics and Bifurcations | 44 |
| 3.2.4 | Modified Switching Rules | 47 |
| 3.2.5 | Manufacturing Systems with Setup Times | 47 |
| 3.3 | Performance of Manufacturing Systems | 48 |
| 3.3.1 | Evaluation of Cost Functions | 49 |
| 3.3.2 | Optimization and Chaos Control | 50 |
| 3.4 | Switched Discrete Deterministic Systems | 51 |
| 3.4.1 | Dynamics | 51 |
| 3.4.2 | Small Stochastic Disturbances | 52 |
| 3.5 | Conclusion | 53 |
| | Bibliography | 53 |

| | | |
|----------|---------------------------------------------------------------------------------------------|-----------|
| 4 | Modeling and Analysis of a Re-entrant Manufacturing System | 55 |
| 4.1 | Introduction | 55 |
| 4.1.1 | Re-entrant Manufacturing Systems and Models | 55 |
| 4.1.2 | Control Policies and Their Analysis | 56 |
| 4.2 | “Two Products – Two Stages” Re-entrant Manufacturing System | 58 |
| 4.3 | Dynamical Model | 59 |
| 4.4 | Analysis of Dynamics | 60 |
| 4.4.1 | Sensitivity to Initial Conditions | 60 |
| 4.4.2 | Ergodicity and Stationarity | 60 |
| 4.4.3 | Correlations | 62 |
| 4.5 | Dynamical Concept for Manufacturing Control | 64 |
| 4.6 | Simulation Model | 65 |
| 4.7 | Analysis of Scheduling Policies | 66 |
| 4.8 | Conclusion and Outlook | 67 |
| | Bibliography | 69 |
| 5 | Nonlinear Models for Control of Manufacturing Systems | 71 |
| 5.1 | Introduction | 71 |
| 5.2 | Extensions to the Standard Fluid Model | 72 |
| 5.2.1 | A Common Fluid Model | 72 |
| 5.2.2 | An Extension | 74 |
| 5.2.3 | An Approximation to the Extended Fluid Model | 75 |
| 5.2.4 | A Hybrid Model | 76 |
| 5.3 | A New Flow Model | 77 |
| 5.3.1 | Introduction to Traffic Flow Theory: the LWR Model | 78 |
| 5.3.2 | A Traffic Flow Model for Manufacturing Flow | 79 |
| 5.4 | The Manufacturing Flow Model Revisited | 80 |
| 5.5 | Concluding Remarks | 81 |
| | Bibliography | 82 |
| 6 | Modeling and Optimization of Production Processes: Lessons from Traffic Dynamics | 85 |
| 6.1 | Modeling the Dynamics of Supply Networks | 85 |
| 6.1.1 | Modeling One-dimensional Supply Chains | 86 |
| 6.1.2 | “Bull-whip Effect” and Stop-and-Go Traffic | 87 |
| 6.1.3 | Dynamical Solution and Resonance Effects | 88 |
| 6.1.4 | Discussion of Some Control Strategies | 90 |
| 6.1.5 | Production Units in Terms of Queueing Theoretical Quantities | 91 |
| 6.1.6 | Calculation of the Cycle Times | 92 |
| 6.1.7 | Feeding Rates, Production Speeds and Inventories | 93 |
| 6.1.8 | Impact of the Supply Network’s Topology | 95 |
| 6.1.9 | Advantages and Extensions | 95 |
| 6.2 | Many-particle Models of Production Processes | 97 |
| 6.2.1 | Learning from Pedestrians | 97 |
| 6.2.2 | Optimal Self-organization and Noise-induced Ordering | 100 |

- 6.2.3 “Slower-is-Faster Effect” in Merging Flows 101
- 6.2.4 Optimization of Multi-object Flows 101
- 6.3 Summary and Outlook 102
- Bibliography 103

II Machine Tools and Manufacturing Processes 107

- 7 Nonlinear Dynamics of High-speed Milling Subjected to Regenerative Effect 111**
 - 7.1 Introduction 111
 - 7.2 Nonlinear Dynamics of Turning 113
 - 7.2.1 Modeling of Turning 113
 - 7.2.2 Bifurcation Analysis of Turning 114
 - 7.2.3 Global Dynamics of Self-interrupted Cutting 116
 - 7.3 Nonlinear Vibrations of High-speed Milling 119
 - 7.3.1 Modeling of High-speed Milling 120
 - 7.3.2 Bifurcation Analysis of High-speed Milling 122
 - 7.3.3 Global Dynamics of Parametrically Interrupted Cutting 126
 - 7.4 Conclusions 126
 - Bibliography 127
- 8 Mode-coupled Regenerative Machine Tool Vibrations 129**
 - 8.1 Introduction 129
 - 8.2 Metal Cutting 130
 - 8.2.1 Oblique Cutting 131
 - 8.3 Three-degree-of-freedom Model of Metal Cutting 132
 - 8.3.1 Cutting Forces 136
 - 8.3.2 The Equations of Motion 137
 - 8.4 Estimation of Model Parameters 138
 - 8.4.1 Structural Parameters 139
 - 8.4.2 Cutting Force Parameters 139
 - 8.4.3 Model Parameters 140
 - 8.5 Analysis of the Model 140
 - 8.5.1 Classical Limit 142
 - 8.5.2 Stability Analysis of the Undamped System Without Delay 142
 - 8.5.3 Stability Analysis of the Two-degree-of-freedom Model with Delay 143
 - 8.6 Conclusions 148
 - Bibliography 149
- 9 Influence of the Workpiece Profile on the Self-excited Vibrations in a Metal Turning Process 153**
 - 9.1 Introduction 153
 - 9.2 Modeling of Turning Process 154
 - 9.3 Analytical Investigations of Primary Cutting 157

| | | |
|-----------|-----------------------------------------------------------------------------------------------------------------------------|------------|
| 9.4 | Numerical Analysis of Primary Cutting | 159 |
| 9.5 | Numerical Investigation of Finishing Cutting Dynamics | 161 |
| 9.6 | Conclusions | 166 |
| | Bibliography | 166 |
| 10 | Modeling of High-speed Milling for Prediction of Regenerative Chatter | 169 |
| 10.1 | Introduction | 169 |
| 10.2 | Modeling | 170 |
| 10.2.1 | Material Model | 172 |
| 10.2.2 | Machine Model | 175 |
| 10.2.3 | The Total Milling Model | 178 |
| 10.3 | Stability Analysis of the Milling System | 179 |
| 10.3.1 | Method of D-partition | 179 |
| 10.4 | Results | 181 |
| 10.5 | Conclusions | 183 |
| | Bibliography | 185 |
| 11 | Nonlinear Dynamics of an External Cylindrical Grinding System and a Strategy for Chatter Compensation | 187 |
| 11.1 | Introduction | 187 |
| 11.2 | Wheel–Workpiece Dynamics | 189 |
| 11.2.1 | Chatter Vibrations | 189 |
| 11.2.2 | Compliance | 190 |
| 11.2.3 | Hilbert Transform | 192 |
| 11.2.4 | Chatter Detection | 192 |
| 11.3 | Modeling of Mechanical Structure Dynamics | 194 |
| 11.3.1 | Model of Guideway Connection | 194 |
| 11.3.2 | Resonances in Guideway System | 197 |
| 11.4 | Feed Drive | 200 |
| 11.4.1 | Requirements for the Infeed Drive | 202 |
| 11.4.2 | Nonlinear Effects and Control Scheme | 203 |
| 11.4.3 | Compensation of Cogging | 203 |
| 11.5 | Waviness Compensation | 205 |
| 11.6 | Conclusions | 206 |
| | Bibliography | 206 |
| 12 | Problems Arising in Finite-Element Simulations of the Chip Formation Process Under High Speed Cutting Conditions | 209 |
| 12.1 | Introduction | 209 |
| 12.2 | Orthogonal Cutting Process | 210 |
| 12.2.1 | Description | 210 |
| 12.2.2 | Material Laws | 210 |
| 12.2.3 | Remeshing and Chip Separation | 212 |
| 12.3 | Simulation Results and the Comparison with Experimental Results | 215 |
| 12.3.1 | Process Parameters | 215 |

- 12.3.2 Cutting Forces and Chip Geometry 217
- 12.3.3 Residual Stresses 220
- 12.3.4 Additional Analysis of the Forming Model 221
- 12.4 Analysis of the Thermal Effects on the Tool 222
- 12.5 3D Model for an Outer Turning Process 223
- 12.6 Conclusions and Outlook 226
- Bibliography 227

13 Finite-element Simulation of Nonlinear Dynamical Effects in Coating–Substrate Systems 229

- 13.1 Introduction 229
- 13.2 Mechanics of Chip Formation in Cutting Processes 230
 - 13.2.1 Basic Assumptions of Modeling 231
 - 13.2.2 Investigations of the Nonlinear Dynamical Cutting Process 233
 - 13.2.3 Results of Nonlinear Dynamical Loading of the Coating–Substrate System 238
- 13.3 Modeling and Simulation of Coating–Substrate Systems 241
 - 13.3.1 3D Coating–Substrate Simulations Based on Parallel Computing 242
 - 13.3.2 Indenter Test Simulation 242
- 13.4 Time Series Analysis 244
- 13.5 Conclusions 246
- Bibliography 246

14 Investigation of Nonlinear Dynamic Effects in Loaded Layer–Substrate Systems Through Molecular Dynamics Simulation 251

- 14.1 Introduction 251
- 14.2 Layer–Substrate System Configuration and Material Representation 252
- 14.3 Properties of the Relaxed System 254
 - 14.3.1 Stress Distributions in the Relaxed System. 254
 - 14.3.2 Interface Properties 256
- 14.4 Response of the Loaded Layer–Substrate System 257
 - 14.4.1 Deformation and Forces 257
 - 14.4.2 Stress Distribution in the Loaded Layer–Substrate System 260
- 14.5 Conclusions 261
- Bibliography 262

15 Simulation, Experimental Investigation and Control of Thermal Behavior in Modular Tool Systems 265

- 15.1 Introduction 265
- 15.2 Investigated Tool Mountings 267
- 15.3 Project Realization 268
 - 15.3.1 Determination of Replacement Heat-transmission Coefficient for Component Joints in a FE Model 268
 - 15.3.2 Building of the Test Stand for Tool Investigations with Fixed Shaft 270
 - 15.3.3 Thermographic Investigations 271

| | | |
|------------|-----------------------------------------------------------------------------------------|------------|
| 15.4 | Maximal Correlation and Optimal Transformations | 273 |
| 15.4.1 | Reconstruction of Thermally Induced Displacements in Finite-element Models | 274 |
| 15.4.2 | Reconstruction of Thermally Induced Displacements in Real Data . . | 278 |
| 15.5 | The Thermal Behavior of a Modular Tool System in a Working Milling Machine | 279 |
| 15.6 | Conclusion | 280 |
| | Bibliography | 283 |
| 16 | Wrinkling in Sheet Metal Spinning | 287 |
| 16.1 | Introduction | 287 |
| 16.2 | Wrinkling in Sheet Metal Spinning | 288 |
| 16.3 | Influence of Nonlinear Dynamic Effects on Wrinkling | 290 |
| 16.4 | The Spinning Process as a Frictional Contact Problem | 292 |
| 16.5 | Time-series Analysis | 295 |
| 16.6 | Finite-element Model | 298 |
| 16.7 | Conclusions | 301 |
| | Bibliography | 302 |
| 17 | Nonlinear Vibrations During the Pass in a Steckel Mill Strip Coiling Process | 305 |
| 17.1 | Introduction | 305 |
| 17.2 | Mechanical Model of the Coiling Process | 306 |
| 17.3 | Results of the Simulation | 311 |
| 17.4 | Conclusion | 315 |
| | Bibliography | 315 |
| III | Dynamics of Robots and Machines | 317 |
| 18 | New Type of Forming Machine | 321 |
| 18.1 | Introduction | 321 |
| 18.2 | Theoretical Analysis of Motion with Rigid Impacts | 323 |
| 18.2.1 | Symmetric Case | 323 |
| 18.2.2 | Asymmetric Cases | 327 |
| 18.3 | Simulations | 330 |
| 18.4 | Experiment | 331 |
| 18.5 | Comparison of Simulation and Experimental Results | 331 |
| 18.6 | Analysis of Motion with Soft Impacts | 333 |
| 18.7 | Conclusion | 336 |
| | Bibliography | 337 |
| 19 | Nonlinear Vibration in Gear Systems | 339 |
| 19.1 | Introduction | 339 |
| 19.2 | One-stage Gear Model | 339 |
| 19.3 | Vibrations of a Gear System in Presence of a Weak Resonance Term | 342 |

| | | |
|-----------|------------------------------------------------------------------------|------------|
| 19.4 | Vibrations of a Gear System with a Flexible Shaft | 344 |
| 19.5 | Conclusions | 345 |
| | Bibliography | 348 |
| 20 | Measurement and Identification of Pre-sliding Friction Dynamics | 349 |
| 20.1 | Introduction | 349 |
| 20.2 | Friction Characterization | 350 |
| 20.2.1 | Friction Model Structures | 351 |
| 20.2.2 | Acquisition of Friction Data | 352 |
| 20.2.3 | Simulation of Friction Data | 353 |
| 20.3 | Identificaton Methods and Results | 354 |
| 20.4 | Regression and Time-Series Modeling | 355 |
| 20.4.1 | NARMAX Models | 355 |
| 20.4.2 | Support Vector Models | 356 |
| 20.4.3 | Local Models | 358 |
| 20.4.4 | Neural Network Methods | 359 |
| 20.4.5 | Numerical Results of Black-box Methods | 360 |
| 20.5 | Identification of Physics-based Models | 361 |
| 20.5.1 | The Linear Regression (LR) Approach | 362 |
| 20.5.2 | The Dynamic Linear Regression (DLR) Approach | 362 |
| 20.5.3 | The Nonlinear Regression (NLR) Approach | 363 |
| 20.5.4 | Model Order Selection and Assessment | 363 |
| 20.5.5 | Identification Results | 364 |
| 20.6 | Discussion and Conclusions | 365 |
| | Bibliography | 366 |
| 21 | Coordination of Mechanical Systems | 369 |
| 21.1 | Introduction | 369 |
| 21.2 | Dynamic Model of the Robot Manipulators | 371 |
| 21.3 | Coordination Controller | 371 |
| 21.3.1 | Feedback-Control Law | 371 |
| 21.3.2 | An Observer for the Coordination Errors (e, \dot{e}) | 372 |
| 21.3.3 | An Observer for the Slave Joint State (q_s, \dot{q}_s) | 372 |
| 21.3.4 | Estimated Values for \dot{q}_m, \ddot{q}_m | 372 |
| 21.3.5 | Ultimate Boundedness of the Closed-loop System | 373 |
| 21.4 | Experimental Case Study | 374 |
| 21.4.1 | Joint Space Dynamics | 375 |
| 21.4.2 | Experimental Results | 376 |
| 21.5 | Conclusions and Further Extensions | 378 |
| | Bibliography | 379 |

| | |
|--------------------------------------------------------------------------------------------|------------|
| IV Non-conventional Manufacturing Processes | 387 |
| 22 Nonlinear Dynamics and Control of Ripple Formation in Abrasive Water-jet Cutting | 391 |
| 22.1 Introduction | 391 |
| 22.2 Phenomenology of Ripple Formation | 392 |
| 22.2.1 Ripple Amplitude and Lag | 393 |
| 22.2.2 Ripple Wavelength | 394 |
| 22.3 Cutting Processes and Pattern Formation | 397 |
| 22.3.1 Pattern Formation by Front Instabilities | 398 |
| 22.3.2 Phenomenological Theory of the Evolution of Cutting Fronts | 400 |
| 22.3.3 Solution of Model Equation | 401 |
| 22.3.4 Spontaneous Ripple Formation | 404 |
| 22.3.5 Suppression of Spontaneous Ripple Formation by Periodic Modulation | 404 |
| 22.4 Experimental Results for Ripple Suppression | 406 |
| 22.5 Conclusions | 408 |
| Bibliography | 409 |
| 23 Modeling and Simulation of Process Monitoring and Control in Laser Cutting | 411 |
| 23.1 Introduction | 411 |
| 23.2 Diagnosis and Analysis of Dynamic Features | 412 |
| 23.3 Coupled Equations of Motion | 414 |
| 23.3.1 Axial Dynamics of the Melting Front | 414 |
| 23.3.2 Lateral Dynamics of the Melting Front | 416 |
| 23.3.3 Melt Flow | 417 |
| 23.4 Heat Convection Influences Ripple Formation | 418 |
| 23.5 Observation of the Cutting Front | 419 |
| 23.6 Quality Classes: Observation and Modeling | 420 |
| 23.7 Control | 421 |
| 23.8 Analysis Using Spectral Methods | 421 |
| 23.9 Conclusion and Outlook | 423 |
| Bibliography | 424 |
| 24 Approximate Model for Laser Welding | 427 |
| 24.1 Introduction | 427 |
| 24.1.1 Technical Motivation and Physical Task | 427 |
| 24.1.2 Asymptotic Methodology | 428 |
| 24.1.3 Former Works | 429 |
| 24.2 Motion of the Melting Front | 429 |
| 24.2.1 Similarities of Thermal Material Processes | 429 |
| 24.2.2 The One-phase problem | 430 |
| 24.2.3 Approximate Equations of Motion | 431 |
| 24.3 Motion of the Capillary | 432 |
| 24.3.1 Experimental Observation and Physical Analysis | 432 |

- 24.3.2 Mathematical Problem Formulation 433
- 24.3.3 Boundary-layer Character of the Melt Flow 434
- 24.3.4 Flow at the Stagnation Point 435
- 24.3.5 Flow Around the Capillary 437
- 24.4 Evaporation 438
- 24.5 Conclusion and Outlook 439
- Bibliography 440

- 25 Short-time Dynamics in Laser Material Processing 443**
- 25.1 Introduction 443
- 25.2 The Free Boundary Problem 444
- 25.3 Finite-dimensional Approximations 447
- 25.4 Conclusion 450
- Bibliography 451

- 26 An Approach to a Process Model of Laser Beam Melt Ablation
Using Methods of Linear and Nonlinear Data Analysis 453**
- 26.1 Introduction 453
- 26.2 Experimental Setup 454
- 26.3 Linear and Nonlinear Data Analysis 455
- 26.4 A Stochastic Process Model 461
- 26.5 Discussion 465
- Bibliography 467

- 27 Dynamics-based Monitoring of Manufacturing Processes:
Detection of Transitions Between Process States 469**
- 27.1 Introduction 469
- 27.2 Information Rate 470
- 27.3 Examples of Transitions 471
 - 27.3.1 Turning 471
 - 27.3.2 Grinding 474
 - 27.3.3 Laser-beam Welding 475
- 27.4 Discussion and Conclusions 478
- Bibliography 479

- V Chemical and Electro-chemical Processes 481**

- 28 Real-time Monitoring of Dynamical State Changes
in Staged Coal Combustion 485**
- 28.1 Introduction 485
- 28.2 Background 486
 - 28.2.1 Practical Approach 492
 - 28.2.2 Example Application 495

| | | |
|-----------|-----------------------------------------------------------------------------------------------------|------------|
| 28.2.3 | Future Developments | 499 |
| 28.2.4 | Broader Implications | 500 |
| | Bibliography | 501 |
| 29 | Towards Constructive Nonlinear Dynamics – Case Studies in Chemical Process Design | 503 |
| 29.1 | Nonlinear Dynamics Analysis in Chemical Engineering | 503 |
| 29.2 | Analysis-based Process Design | 505 |
| 29.2.1 | Illustrative Example | 506 |
| 29.2.2 | Continuation Analysis | 507 |
| 29.3 | Analysis-based Control System Design | 509 |
| 29.3.1 | Illustrative Example | 509 |
| 29.3.2 | Controller Tuning Procedure | 512 |
| 29.4 | Limitations of Analysis-based Design | 513 |
| 29.5 | Constructive Methods | 516 |
| 29.5.1 | Normal Vector-based Constraints for Parametric Robustness | 517 |
| 29.5.2 | Optimization with Robust Stability and Feasibility Constraints | 520 |
| 29.5.3 | Optimization with Parametric Robustness with Respect to Hysteresis | 522 |
| 29.6 | Summary and Outlook | 524 |
| | Bibliography | 524 |
| 30 | Nonlinear Dynamics in Chemical Engineering and Electro-chemical Manufactory Technologies | 527 |
| 30.1 | Introduction | 527 |
| 30.2 | Electropolishing | 528 |
| 30.3 | Surface Structuring by Micro-electropolishing | 533 |
| 30.4 | Etching Processes: Structure Formation on the Rotating Disk Electrode | 534 |
| 30.5 | Oscillating BZ Reactors Coupled via Liquid Membranes | 538 |
| 30.6 | Reaction in Mono-porous Foams | 543 |
| 30.7 | Conclusion | 551 |
| | Bibliography | 552 |
| 31 | Galvanostatic Studies of an Oxygen-evolving Electrode | 559 |
| 31.1 | Introduction | 559 |
| 31.1.1 | N-NDR and N-HNDR Behavior | 560 |
| 31.2 | Experimental | 560 |
| 31.3 | Results | 562 |
| 31.3.1 | Cyclic Voltammogram | 562 |
| 31.3.2 | Methanol and Ethanol | 563 |
| 31.3.3 | Butanol/Standard | 565 |
| 31.3.4 | Phosphoric Acid | 568 |
| 31.4 | Conclusion | 570 |
| | Bibliography | 572 |

| | |
|------------------------------------------------------------------------------|------------|
| 32 Wavelet Analysis of Electropolished Surfaces | 575 |
| 32.1 Introduction | 575 |
| 32.2 The Experimental Setup | 577 |
| 32.3 Continuous Wavelet Transform | 578 |
| 32.4 Characteristic Length Scales and Scaling Regions | 580 |
| 32.5 Multi-fractal Analysis | 582 |
| 32.6 Stochastic Analysis | 586 |
| 32.7 Conclusions | 589 |
| Bibliography | 590 |
| | |
| 33 Spatial Inhomogeneity in Lead–Acid Batteries | 593 |
| 33.1 Introduction | 593 |
| 33.2 Experimental | 595 |
| 33.2.1 Local Potential Measurements with Ag/AgCl Electrodes | 595 |
| 33.2.2 Local Potential Measurements with Auxiliary Lead Electrodes | 596 |
| 33.3 Results and Discussion | 597 |
| 33.3.1 Local Potential Measurements with Ag/AgCl Electrodes | 597 |
| 33.3.2 Local Potential Measurements with Lead Electrodes | 601 |
| 33.4 Conclusions and Future Work | 604 |
| Bibliography | 604 |
| | |
| Index | 607 |

