John Guckenheimer Philip Holmes

# Nonlinear Oscillations, Dynamical Systems, and Bifurcations of Vector Fields

With 206 Illustrations



John Guckenheimer Philip Holmes Department of Mathematics Department of Mechanical Cornell University and Aerospace Engineering and Ithaca, NY 14853 Program in Applied and USA Computational Mathematics gucken@cam.cornell.edu Princeton University Princeton, NJ 08544 USA pholmes@rimbaud.princeton.edu Editors J.E. Marsden L. Sirovich Control and Dynamical Systems, 107-81 Division of Applied Mathematics California Institute of Technology Brown University Pasadena, CA 91125 Providence, RI 02912 USA USA

Mathematics Subject Classification (2000): 34A34, 34C15, 34C35, 5

Library of Congress Cataloging-in-Publication Data
Guckenheimer, John.
Nonlinear oscillations, dynamical systems and bifurcations of vector fields.
(Applied mathematical sciences ; v. 42)
Bibliography : p.
Includes index.
1. Nonlinear oscillations.
2. Differentiable
dynamical systems.
3. Bifurcation theory.
4. Vector
fields.
I. Holmes, Philip.
II. Title.
III. Series:
Applied mathematical sciences (Springer Science+Business Media, LLC); v.42.
QA1.A647 vol. 42 [QA867.5] 510s [531'.322] 82-19641

#### © 1983 Springer Science+Business Media New York Originally published by Springer-Verlag New York, Inc. in 1983 Softcover reprint of the hardcover 1st edition 1983

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, 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 of general descriptive names, trade names, trademarks, etc., in this publication, even if the former are not especially identified, is not to be taken as a sign that such names, as understood by the Trade Marks and Merchandise Marks Act, may accordingly be used freely by anyone.

Typeset by Composition House Ltd., Salisbury, England.

9 8 7 (Corrected seventh printing, 2002)

ISBN 978-1-4612-7020-1 ISBN 978-1-4612-1140-2 (eBook) DOI 10.1007/978-1-4612-1140-2

## Contents

### CHAPTER 1

Introduction: Differential Equations and Dynamical Systems	1
1.0. Existence and Uniqueness of Solutions	1
1.1. The Linear System $\dot{x} = Ax$	8
1.2. Flows and Invariant Subspaces	10
1.3. The Nonlinear System $\dot{x} = f(x)$	12
1.4. Linear and Nonlinear Maps	16
1.5. Closed Orbits, Poincaré Maps, and Forced Oscillations	22
1.6. Asymptotic Behavior	33
1.7. Equivalence Relations and Structural Stability	38
1.8. Two-Dimensional Flows	42
1.9. Peixoto's Theorem for Two-Dimensional Flows	60

#### CHAPTER 2

An Introduction to Chaos: Four Examples	66
2.1. Van der Pol's Equation	67
2.2. Duffing's Equation	82
2.3. The Lorenz Equations	92
2.4. The Dynamics of a Bouncing Ball	102
2.5. Conclusions: The Moral of the Tales	116

#### CHAPTER 3

Local Bifurcations	117
3.1. Bifurcation Problems	118
3.2. Center Manifolds	123
3.3. Normal Forms	138
3.4. Codimension One Bifurcations of Equilibria	145
3.5. Codimension One Bifurcations of Maps and Periodic Orbits	156

Averaging and Perturbation from a Geometric Viewpoint	166
4.1. Averaging and Poincaré Maps	167
4.2. Examples of Averaging	171
4.3. Averaging and Local Bifurcations	178
4.4. Averaging, Hamiltonian Systems, and Global Behavior:	1/0
Cautionary Notes	180
4.5. Melnikov's Method: Perturbations of Planar Homoclinic Orbits	184
4.6. Melnikov's Method: Perturbations of Hamiltonian Systems and	104
Subharmonic Orbits	193
4.7. Stability of Subharmonic Orbits	205
4.8. Two Degree of Freedom Hamiltonians and Area Preserving Maps	205
of the Plane	212
	212
CHAPTER 5	
Hyperbolic Sets, Symbolic Dynamics, and Strange Attractors	227
5.0. Introduction	227
5.1. The Smale Horseshoe: An Example of a Hyperbolic Limit Set	230
5.2. Invariant Sets and Hyperbolicity	235
5.3. Markov Partitions and Symbolic Dynamics	248
5.4. Strange Attractors and the Stability Dogma	255
5.5. Structurally Stable Attractors	259
5.6. One-Dimensional Evidence for Strange Attractors	268
5.7. The Geometric Lorenz Attractor	273
5.8. Statistical Properties: Dimension, Entropy, and Liapunov Exponents	280
CHAPTER 6	
Global Bifurcations	289
6.1. Saddle Connections	290
6.2. Rotation Numbers	295
6.3. Bifurcations of One-Dimensional Maps	306
6.4. The Lorenz Bifurcations	312
6.5. Homoclinic Orbits in Three-Dimensional Flows: Šilnikov's Example	318
6.6. Homoclinic Bifurcations of Periodic Orbits	325
6.7. Wild Hyperbolic Sets	331
6.8. Renormalization and Universality	342
-	542
CHAPTER 7	2.52
Local Codimension Two Bifurcations of Flows	353
7.1. Degeneracy in Higher-Order Terms	354
7.2. A Note on $k$ -Jets and Determinacy	360
7.3. The Double Zero Eigenvalue	364
7.4. A Pure Imaginary Pair and a Simple Zero Eigenvalue	376
7.5. Two Pure Imaginary Pairs of Eigenvalues without Resonance	396
7.6. Applications to Large Systems	411
APPENDIX	
Suggestions for Further Reading	421
Postscript Added at Second Printing	425
Glossary	431
References	437
	455
Index	455