Hydrodynamic Instabilities and the Transition to Turbulence

Edited by H. L. Swinney and J. P. Gollub

With Contributions by
F. H. Busse P. A. Davies R. C. Di Prima J. P. Gollub
J. M. Guckenheimer D. D. Joseph O. E. Lanford
S. A. Maslowe H. L. Swinney D. J. Tritton
E. D. Yorke J. A. Yorke

Second Edition

With 82 Figures

Springer-Verlag
Berlin Heidelberg New York Tokyo

Professor *Harry L. Swinney*, PhD

The University of Texas at Austin, Department of Physics,
Austin, TX 78712, USA

Professor *Jerry P. Gollub*, PhD

Department of Physics, Haverford College,
Haverford, PA 19041, USA and
Department of Physics, University of Pennsylvania,
Philadelphia, PA 19104 USA

ISBN 3-540-13319-4 2. Auflage Springer-Verlag Berlin Heidelberg New York Tokyo
ISBN 0-387-13319-4 2nd edition Springer-Verlag New York Heidelberg Berlin Tokyo

ISBN 3-540-10390-2 1. Auflage Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-10390-2 1st edition Springer-Verlag New York Heidelberg Berlin

Library of Congress Cataloging in Publication Data. Main entry under title: Hydrodynamic instabilities and the transition to turbulence. (Topics in applied physics; v. 45) Includes bibliographies and index. 1. Hydrodynamics. 2. Stability. 3. Turbulence. I. Swinney, H.L., 1939–. II. Gollub, J.P., 1944–. III. Title: Hydrodynamic instabilities. IV. Series. QA911.H9 1985 532'.5 85-2851

Monophoto typesetting, offset printing and bookbinding: Brühlsche Universitätsdruckerei, Giessen
2153/3130-543210

Preface to the Second Edition

In the four years that have elapsed between the first and second editions of this book, much progress has been made in understanding hydrodynamic instabilities and the transition to turbulence. For example, the strange attractors discussed theoretically by Lanford in Chap. 2 have been convincingly observed in experiments on weakly turbulent flows, and several "universal" routes to chaos have been identified in theoretical and experimental studies. Many other noteworthy advances have been made using quite different theoretical methods. For example, the evolution of convection patterns has been studied using two-dimensional model equations.

Brief descriptions of these and other developments, along with numerous added references, are included in this second edition. We hope that the reduced cost of this edition in paperback will make it accessible to many additional scientists and students in the various fields to which it is relevant, especially physics, mathematics, and engineering.

We appreciate the assistance of our contributors, and the support of the National Science Foundation Fluid Mechanics Program.

We dedicate this book to the memory of our colleague and friend, Richard C. DiPrima (9 August 1927–10 September 1984), whose contributions to hydrodynamic stability theory will long be remembered.

Austin and Haverford, February 1985 *H. L. Swinney · J. P. Gollub*

Preface to the First Edition

Although much of the universe is filled with fluids in turbulent motion, the processes by which turbulence develops are poorly understood. When a fluid is driven away from thermal and mechanical equilibrium, it will often undergo a sequence of instabilities, each of which leads to a change in the spatial or temporal structure of the flow. The nature of these instabilities, which sometimes lead to turbulence, is the subject of this volume.

Hydrodynamic instabilities and turbulence have been extensively studied for more than a century, but the research has been primarily concerned with either the first instability that occurs with increasing Reynolds number or with turbulence at very large Reynolds number. The transition from laminar to turbulent flow has until recently been largely beyond the reach of both theory and experiment. This situation has been changed dramatically by the use of computers in laboratory experiments and in numerical analyses of nonlinear systems. While past experiments were primarily photographic or measured time-averaged quantities, recent experiments using computers and modern optical and cryogenic techniques have distinguished between many different dynamical regimes of flows undergoing transition. Numerical studies of nonlinear models have also revealed entirely unexpected results, such as chaotic behavior in a system with only three variables. Another development of great potential importance is the application of new mathematical concepts from the qualitative theory of differential equations, sometimes known as dynamical systems theory, to the transition to turbulence problem. More traditional methods such as bifurcation theory and stability analysis also continue to contribute major new insights.

This book is a collaboration between physicists, mathematicians, and fluid dynamicists, each of whom is a recognized leader in the field. The various chapters include: introductions to the relationship between dynamical systems theory and turbulence (Chaps. 2 and 4); a review of hydrodynamic stability and bifurcation theory (Chap. 3); three case studies – convection, rotating fluids, and shear flows (Chaps. 5–7); a review of the many types of instabilities that occur in geophysics (Chap. 8); and a discussion of instabilities and chaotic behavior in nonhydrodynamic systems (Chap. 9).

Although not all of the book is strictly introductory, the authors have tried to make the majority of it accessible to physicists, mathematicians, engineers, and graduate students who do not have significant background in fluid dynamics and advanced mathematics. It is our hope that it will provide an introduction to the literature of this rapidly developing field.

We owe special thanks to D. D. Joseph for his encouragement and advice in this endeavor, and to our contributors for their efforts to communicate with clarity to a new audience. We also acknowledge the support of the National Science Foundation.

Austin and Haverford, October 1980 *H. L. Swinney · J. P. Gollub*

Contents

Contributors

Busse, Friedrich H.
Department of Earth and Space Science and
Institute of Geophysics and Planetary Physics, University of California
Los Angeles, CA 90024, USA

Davies, Peter A.
Department of Civil Engineering, University of Dundee
Dundee DD1 4HN, UK

DiPrima, Richard C. (deceased)

Gollub, Jerry P.
Department of Physics, Haverford College
Haverford, PA 19041, USA and
Department of Physics, University of Pennsylvania
Philadelphia, PA 19104 USA

Guckenheimer, John M.
Department of Mathematics, Cornell University
Ithaca, NY 14853, USA

Joseph, Daniel D.
Department of Aerospace Engineering and Mechanics
University of Minnesota,
Minneapolis, MN 55455, USA

Lanford, Oscar E.
I.H.E.S., F-91440 Bures-sur-Yvette, France

Maslowe, Sherwin A.
Mathematics Department, McGill University, 805 Sherbrooke Street West
Montreal H3A 2K6, Canada

Swinney, Harry L.
The University of Texas at Austin, Department of Physics
Austin, TX 78712, USA

Tritton, David J.
School of Physics, The University
Newcastle upon Tyne NE1 7RU, England

Yorke, Ellen D.
Department of Physics, University of Maryland Baltimore County
Catonsville, MD 21228, USA

Yorke, James A.
Institute for Physical Science and Technology
University of Maryland, College Park, MD 20742, USA