Pijush K. Kundu Ira M. Cohen David R. Dowling
with contributions by P.S. Ayyaswamy and H.H. Hu

Fluid Mechanics

流体力学 第5版

Fifth Edition

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FIFTH EDITION

PIJUSH K. KUNDU
IRA M. COHEN
DAVID R. DOWLING

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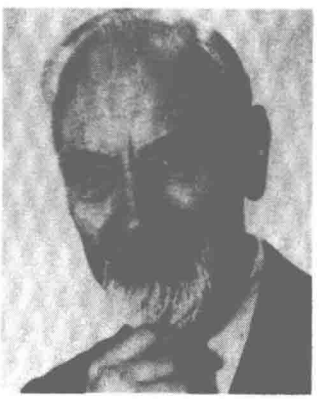
FLUID MECHANICS

FIFTH EDITION

Founders of Modern Fluid Dynamics



Ludwig Prandtl
(1875-1953)

G. I. Taylor
(1886-1975)

(Biographical sketches of Prandtl and Taylor are given in Appendix C.)

Dedication

This revision to this textbook is dedicated to my wife and family who have patiently helped chip many sharp corners off my personality, and to the many fine instructors and students with whom I have interacted who have all in some way highlighted the allure of this subject for me.

D.R.D.

In Memory of Pijush Kundu

Pijush Kanti Kundu was born in Calcutta, India, on October 31, 1941. He received a BS degree in Mechanical Engineering in 1963 from Shibpur Engineering College of Calcutta University, earned an MS degree in Engineering from Roorkee University in 1965, and was a lecturer in Mechanical Engineering at the Indian Institute of Technology in Delhi from 1965 to 1968. Pijush came to the United States in 1968, as a doctoral student at Penn State University. With Dr. John L. Lumley as his advisor, he studied instabilities of viscoelastic fluids, receiving his doctorate in 1972. He began his lifelong interest in oceanography soon after his graduation, working as Research Associate in Oceanography at Oregon State University from 1968 until 1972. After spending a year at the University de Oriente in Venezuela, he joined the faculty of the Oceanographic Center of Nova Southeastern University, where he remained until his death in 1994.

During his career, Pijush contributed to a number of sub-disciplines in physical oceanography, most notably in the fields of coastal dynamics, mixed-layer physics, internal waves, and Indian-Ocean dynamics. He was a skilled data analyst, and, in this regard, one of his accomplishments was to introduce the "empirical orthogonal eigenfunction" statistical technique to the oceanographic community.

I arrived at Nova Southeastern University shortly after Pijush, and he and I worked closely together thereafter. I was immediately impressed with the clarity of his scientific thinking and his thoroughness. His most impressive and obvious quality, though, was his love of science, which pervaded all his activities. Some time after we met, Pijush opened a drawer in a desk in his home office, showing me drafts of several chapters to a book he had always wanted to write. A decade later, this manuscript became the first edition of *Fluid Mechanics*, the culmination of his lifelong dream, which he dedicated to the memory of his mother, and to his wife Shikha, daughter Tonushree, and son Joydip.

Julian P. McCreary, Jr.,
University of Hawaii

In Memory of Ira Cohen

Ira M. Cohen earned his BS from Polytechnic University in 1958 and his PhD from Princeton University in 1963, both in aeronautical engineering. He taught at Brown University for three years prior to joining the University of Pennsylvania faculty as an assistant professor in 1966. He served as chair of the Department of Mechanical Engineering and Applied Mechanics from 1992 to 1997.

Professor Cohen was a world-renowned scholar in the areas of continuum plasmas, electrostatic probe theories and plasma diagnostics, dynamics and heat transfer of lightly ionized gases, low current arc plasmas, laminar shear layer theory, and matched asymptotics in fluid mechanics. Most of his contributions appear in the *Physics of Fluids* journal of the American Institute of Physics. His seminal paper, "Asymptotic theory of spherical electrostatic probes in a slightly ionized, collision dominated gas" (1963; *Physics of Fluids, 6,* 1492–1499), is to date the most highly cited paper in the theory of electrostatic probes and plasma diagnostics.

During his doctoral work and for a few years beyond that, Ira collaborated with a world-renowned mathematician/physicist, the late Dr. Martin Kruskal (recipient of National Medal of Science, 1993) on the development of a monograph called "Asymptotology." Professor Kruskal also collaborated with Professor Cohen on plasma physics. This was the basis for Ira's strong foundation in fluid dynamics that has been transmitted into the prior editions of this textbook.

In his forty-one years of service to the University of Pennsylvania before his death in December 2007, Professor Cohen distinguished himself with his integrity, his fierce defense of high scholarly standards, and his passionate commitment to teaching. He will always be remembered for his candor and his sense of humor.

Professor Cohen's dedication to academics was unrivalled. In addition, his passion for physical fitness was legendary. Neither rain nor sleet nor snow would deter him from his daily bicycle commute, which began at 5:00 AM, from his home in Narberth to the University of Pennsylvania. His colleagues grew accustomed to seeing him drag his forty-year-old bicycle, with its original

three-speed gearshift, up to his office. His other great passion was the game of squash, which he played with extraordinary skill five days a week at the Ringe Squash Courts at Penn, where he was a fierce but fair competitor. During the final year of his life, Professor Cohen remained true to his bicycling and squash-playing schedule, refusing to allow his illness get in the way of the things he loved.

Professor Cohen was a member of Beth Am Israel Synagogue, and would on occasion lead Friday night services there. He and his wife, Linda, were first married near Princeton, New Jersey, on February 13, 1960, when they eloped. They were married a second time four months later in a formal ceremony. He is survived by his wife, his two children, Susan Cohen Bolstad and Nancy Cohen Cavanaugh, and three grandchildren, Melissa, Daniel, and Andrew.

Senior Faculty
Department of Mechanical Engineering
and Applied Mechanics
University of Pennsylvania

About the Third Author

David R. Dowling was born in Mesa, Arizona, in 1960 but grew up in southern California where early practical exposure to fluid mechanics—swimming, surfing, sailing, flying model aircraft, and trying to throw a curve ball—dominated his free time. He attended the California Institute of Technology continuously for a decade starting in 1978, earning a BS degree in Applied Physics in 1982, and MS and PhD degrees in Aeronautics in 1983 and 1988, respectively. After graduate school, he worked at Boeing Aerospace and Electronics and then took a post-doctoral scientist position at the Applied Physics Laboratory of the University of Washington. In 1992, he started a faculty career in the Department of Mechanical Engineering at the University of Michigan where he has since taught and conducted research in fluid mechanics and acoustics. He has authored and co-authored more than 60 archival journal articles and more than 100 conference presentations. His published research in fluid mechanics includes papers on turbulent mixing, forced-convection heat transfer, cirrus clouds, molten plastic flow, interactions of surfactants with water waves, and hydrofoil performance and turbulent boundary layer characteristics at high Reynolds numbers. From January 2007 through June 2009, he served as an Associate Chair and as the Undergraduate Program Director for the Department of Mechanical Engineering at the University of Michigan. He is a fellow of the American Society of Mechanical Engineers and of the Acoustical Society of America. He received the Student Council Mentoring Award of the Acoustical Society of America in 2007, the University of Michigan College of Engineering John R. Ullrich Education Excellence Award in 2009, and the Outstanding Professor Award from the University of Michigan Chapter of the American Society for Engineering Education in 2009. Prof. Dowling is an avid swimmer, is married, and has seven children.

About the DVD

We are pleased to include a free copy of the DVD *Multimedia Fluid Mechanics*, 2/e, with this copy of *Fluid Mechanics, Fifth Edition*. You will find it in a plastic sleeve on the inside back cover of the book. If you are purchasing a used copy, be aware that the DVD might have been removed by a previous owner.

Inspired by the reception of the first edition, the objectives in *Multimedia Fluid Mechanics*, 2/e, remain to exploit the moving image and interactivity of multimedia to improve the teaching and learning of fluid mechanics in all disciplines by illustrating fundamental phenomena and conveying fascinating fluid flows for generations to come.

The completely new edition on the DVD includes the following:

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- Four times the number of fluid videos, now more than 800
- Now more than 20 virtual labs and simulations
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Additional *new* features:

- Improved navigation via sidebars that provide rapid overviews of modules and guided browsing
- Media libraries for each chapter that give a snapshot of videos, each with descriptive labels
- Ability to create movie playlists, which are invaluable in teaching
- Higher-resolution graphics, with full or part screen viewing options
- Operates on either a PC or a Mac OSX

Preface

In the fall of 2009, Elsevier approached me about possibly taking over as the lead author of this textbook. After some consideration and receipt of encouragement from faculty colleagues here at the University of Michigan and beyond, I agreed. The ensuing revision effort then tenaciously pulled all the slack out of my life for the next 18 months. Unfortunately, I did not have the honor or pleasure of meeting or knowing either prior author, and have therefore missed the opportunity to receive their advice and guidance. Thus, the revisions made for this *5th Edition* of *Fluid Mechanics* have been driven primarily by my experience teaching and interacting with undergraduate and graduate students during the last two decades.

Overall, the structure, topics, and technical level of the *4th Edition* have been largely retained, so instructors who have made prior use of this text should recognize much in the *5th Edition*. This textbook should still be suitable for advanced-undergraduate or beginning-graduate courses in fluid mechanics. However, I have tried to make the subject of fluid mechanics more accessible to students who may have only studied the subject during one prior semester, or who may need fluid mechanics knowledge to pursue research in a related field.

Given the long history of this important subject, this textbook (at best) reflects one evolving instructional approach. In my experience as a student, teacher, and faculty member, a textbook is most effective when used as a supporting pedagogical tool for an effective lecturer. Thus my primary revision objective has been to improve the text's overall utility to students and instructors by adding introductory material and references to the first few chapters, by increasing the prominence of engineering applications of fluid mechanics, and by providing a variety of new exercises (more than 200) and figures (more than 100). For the chapters receiving the most attention (1–9, 11–12, and 14) this has meant approximately doubling, tripling, or quadrupling the number of exercises. Some of the new exercises have been built from derivations that previously had appeared in the body of the text, and some involve simple kitchen or bathroom experiments. My hope for a future edition is that there will be time to further expand the exercise offerings, especially in Chapters 10, 13, 15, and 16.

In preparing this *5th Edition*, some reorganization, addition, and deletion of material has also taken place. Dimensional analysis has been moved to Chapter 1. The stream function's introduction and the dynamic-similarity topic have been moved to Chapter 4. Reynolds transport theorem now occupies the final section of Chapter 3. The discussion of the wave equation has been placed in the acoustics section of Chapter 15. Major topical additions are: apparent mass (Chapter 6), elementary lubrication theory (Chapter 8), and Thwaites method (Chapter 9). The sections covering the laminar shear layer, and boundary-layer theory from a purely mathematical perspective, and coherent structures in wall-bounded turbulent flow have

been removed. The specialty chapters (10, 13, and 16) have been left largely untouched except for a few language changes and appropriate renumbering of equations. In addition, some sections have been combined to save space, but this has been offset by an expansion of nearly every figure caption and the introduction of a nomenclature section with more than 200 entries.

Only a few notation changes have been made. Index and vector notation predominate throughout the text. The comma notation for derivatives now only appears in Section 5.6. The notation for unit vectors has been changed from bold **i** to bold **e** to conform to other texts in physics and engineering. In addition, a serious effort was made to denote two- and three-dimensional coordinate systems in a consistent manner from chapter to chapter. However, the completion of this task, which involves retyping literally hundreds of equations, was not possible in the time available. Thus, cylindrical coordinates (R, φ, z) predominate, but (r, θ, x) still appear in Table 12.1, Chapter 16, and a few other places.

And, as a final note, the origins of many of the new exercises are referenced to individuals and other sources via footnotes. However, I am sure that such referencing is incomplete because of my imperfect memory and record keeping. Therefore, I stand ready to correctly attribute the origins of any problem contained herein. Furthermore, I welcome the opportunity to correct any errors you find, to hear your opinion of how this book might be improved, and to include exercises you might suggest; just contact me at *drd@umich.edu*.

David R. Dowling
Ann Arbor, Michigan
April 2011

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An updated errata sheet is available on the book's companion website. To access the errata, visit www.elsevierdirect.com/9780123821003 and click on the companion site link. Instructors teaching with this book may access the solutions manual and image bank by visiting www.textbooks.elsevier.com and following the online instructions to log on and register.