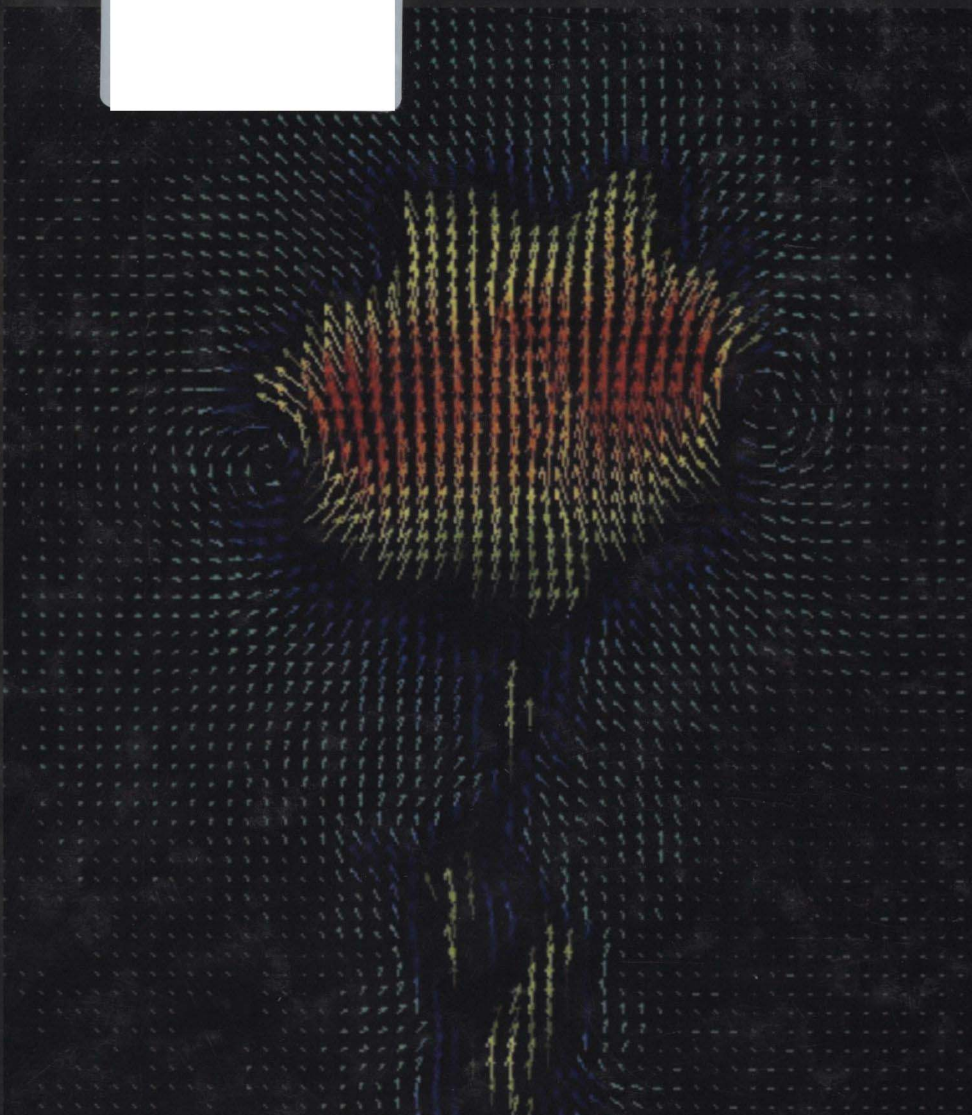
# SYNTHETIC JETS

## Fundamentals and Applications



Edited by

Kamran Mohseni
Rajat Mittal

CRC Press
Taylor & Francis Group

# SYNTHETIC JETS
## Fundamentals and Applications

Edited by
Kamran Mohseni
Rajat Mittal



CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742



Printed on acid-free paper
Version Date: 20140801

International Standard Book Number-13: 978-1-4398-6810-2 (Hardback)



**Library of Congress Cataloging-in-Publication Data**

Synthetic jets : fundamentals and applications / editors, Kamran Mohseni, Rajat Mittal.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4398-6810-2 (hardcover : alk. paper) 1. Axial flow. 2. Jets--Fluid dynamics. I. Mohseni, Kamran. II. Mittal, Rajat.

TA357.5.A95S96 2015
621.6'91--dc23 2014024202

**Visit the Taylor & Francis Web site at**
**http://www.taylorandfrancis.com**

**and the CRC Press Web site at**
**http://www.crcpress.com**

# SYNTHETIC JETS

*.....to our families*

# Preface

Synthetic jets have been the subject of intense research and development for over two decades and have in this time been deployed in a wide variety of applications, ranging from separation and turbulence control to electronic cooling and propulsion. These jets are characterized by the fact that they are entirely synthesized from the surrounding fluid and introduce no net mass into the external flow. This fact eliminates the need for fluidic circuitry and enables self-contained, compact designs that integrate power and actuation and even control electronics. Although synthetic jets do not inject net mass, they do impart momentum, energy, and vorticity, and in doing so, effect local as well as global modifications in the external flow. The ability to prescribe and/or modify the jet frequency and amplitude as well as tailor the geometry of the jet opens up a vast parameter space that can be exploited in a diverse range of applications. This large operational space is, however, associated with a rich cornucopia of fluid dynamic mechanisms, and these mechanisms have to be understood well, in order to make effective use of these actuators in any given application.

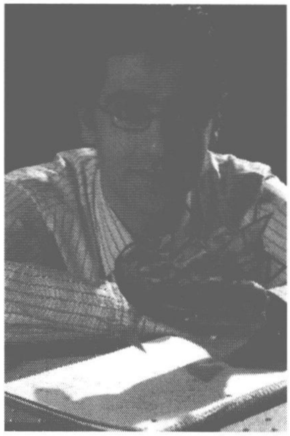
Although the topic of synthetic jets may have matured to some degree, the scientific knowledge associated with these actuators remains scattered across hundreds of journal articles and conference papers. The objective of this book is to compile in one place fundamental as well as applied knowledge of these fluidic actuators. By providing a concise survey of the fundamental principles and analysis techniques, and a few selected applications, this book offers a treatment of the subject that should serve as a useful starting point for students, researchers, and technologists interested in this topic.

**Kamran Mohseni**
*University of Florida*

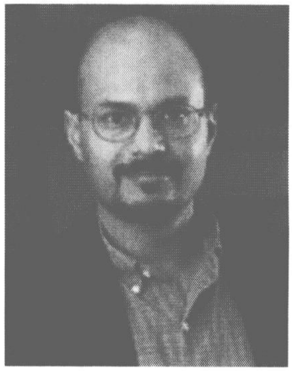
**Rajat Mittal**
*The Johns Hopkins University*

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098 USA
Tel: +1 508 647 7000
Fax: +1 508 647 7001
E-mail: info@mathworks.com
Web: www.mathworks.com

# Editors



**Kamran Mohseni**, who received his PhD in Mechanical Engineering from the California Institute of Technology in 2000, is professor and W.P. Bushnell endowed chair in the Department of Mechanical and Aerospace Engineering and in the Department of Electrical and Computer Engineering at the University of Florida in Gainesville. He is also the director of the Institute for Networked Autonomous Systems there. He was previously associate professor of Aerospace Engineering Sciences, University of Colorado at Boulder, as well as courtesy professor in the Departments of Electrical Engineering and Mechanical Engineering, and an affiliated faculty of the Department of Applied Mathematics. He was also a founding fellow of the Renewable and Sustainable Energy Institute (RASEI), a joint partnership with the National Renewable Energy Laboratory (NREL) in the Department of Energy. He earned his doctorate from the California Institute of Technology in Mechanical Engineering and his masters from Imperial College London in Aeronautics and Applied Mathematics. His research interests include bioinspired unmanned aerial and underwater vehicles, vehicle system dynamics and control, mobile sensor networking, and fluid dynamics. He is an associate fellow of the American Institute of Aeronautics and Astronautics and a member of other professional societies, including the American Physical Society, American Society of Mechanical Engineers, Society for Industrial and Applied Mathematics, Institute of Electrical and Electronics Engineers, and American Geophysical Union.



**Rajat Mittal** is professor in the department of mechanical engineering at the Johns Hopkins University in Baltimore, Maryland. He earned his PhD in applied mechanics from the University of Illinois at Urbana–Champaign and his masters in aerospace engineering from the University of Florida in Gainesville, Florida. He was a postdoctoral researcher in the Center for Turbulence Research at Stanford University before joining the University of Florida's department of mechanical engineering as an assistant professor. He was then appointed as faculty in the department of mechanical and aerospace engineering at The George Washington University in Washington, DC. His research focuses on computational fluid dynamics, low Reynolds number aerodynamics, biomedical flows, active flow control, biomimetics and bioinspired engineering, and fluid dynamics of locomotion. He is a fellow of the American Society of Mechanics Engineers as well as the American Physical Society, and an associate fellow of the American Institute of Aeronautics and Astronautics.

# Contributors

**Michael Amitay**
Department of Mechanical, Aerospace and Nuclear Engineering
Rensselaer Polytechnic Institute
Troy, New York

**Shawn Aram**
Department of Mechanical Engineering
The Johns Hopkins University
Baltimore, Maryland

**Mehmet Arik**
Department of Mechanical Engineering
Özyeğin University
Istanbul, Turkey

**Louis N. Cattafesta**
Department of Mechanical Engineering
Florida State University
Tallahassee, Florida

**John Farnsworth**
Department of Mechanical, Aerospace and Nuclear Engineering
Rensselaer Polytechnic Institute
Troy, New York

**Mike Krieg**
Department of Mechanical and Aerospace Engineering
University of Florida
Gainesville, Florida

**Rajat Mittal**
Department of Mechanical Engineering
The Johns Hopkins University
Baltimore, Maryland

**Kamran Mohseni**
Department of Mechanical and Aerospace Engineering and Department of Electrical and Computer Engineering
University of Florida
Gainesville, Florida

**Reni Raju**
Department of Mechanical and Aerospace Engineering
The George Washington University
Washington, DC

**Barton L. Smith**
Department of Mechanical and Aerospace Engineering
Utah State University
Logan, Utah

**Douglas R. Smith**
Air Force Office of Scientific Research
Arlington, Virginia

**Yogen V. Utturkar**
GE Global Research Center
Electronics Cooling Laboratory
Niskayuna, New York

**David R. Williams**
Fluid Dynamics Research Center
Department of Mechanical, Materials, and Aerospace Engineering
Illinois Institute of Technology
Chicago, Illinois

**Nail K. Yamaleev**
Department of Mathematics
North Carolina A&T State University
Greensboro, North Carolina

**Shan Zhong**
School of Mechanical, Aerospace and Civil Engineering
University of Manchester
Manchester, England

# Contents

Preface ........................................................ ix

Editors ........................................................ xi

Contributors ........................................................ xiii

## SECTION I Fundamentals

1 Synthetic Jets: Basic Principles ........................................ 3
*Kamran Mohseni and Rajat Mittal*

2 Design of Synthetic Jets ........................................ 49
*Louis N. Cattafesta*

## SECTION II Techniques

3 Measurement Techniques for Synthetic Jets ........................ 101
*Barton L. Smith and Douglas R. Smith*

4 Computational Modeling of Synthetic Jets ........................ 129
*Rajat Mittal, Shawn Aram, and Reni Raju*

5 Reduced-Order Modeling of Synthetic Jets ........................ 165
*Nail K. Yamaleev*

## SECTION III Applications

6 Separation Control ........................................ 193
*Michael Amitay and John Farnsworth*

7 Application of Synthetic Jets to Controlling Dynamically Changing Flows ........ 235
*David R. Williams*

8 Synthetic Jets in Boundary Layers ........ 259
*Shan Zhong*

9 Synthetic Jets for Heat Transfer Augmentation ........ 293
*Mehmet Arik and Yogen V. Utturkar*

10 Application of Zero-Net Mass-Flux Actuators for Propulsion: Biology and Engineering ........ 329
*Mike Krieg and Kamran Mohseni*

**Index** ........ 361

# I

# Fundamentals

1 **Synthetic Jets: Basic Principles** *Kamran Mohseni and Rajat Mittal* .... 3
Preliminaries • SJ Modeling

2 **Design of Synthetic Jets** *Louis N. Cattafesta* ..........................49
Introduction • Actuator Components • Performance Metrics • Design/Implementation Issues • Design Tool • Sample Designs • Lumped Element Modeling Limitations • Design Trade-Offs and Optimization • Future Trends