Ethirajan Rathakrishnan

Hypersonic Slender Body Aerodynamics

Aerospace Series

Editors Peter Belobaba, Jonathan Cooper and Allan Seabridge

with website

WILEY

Hypersonic Slender Body Aerodynamics

Aerospace Series

Hypersonic Slender Body Aerodynamics
Ethirajan Rathakrishnan

Aircraft System Classifications: A Handbook of Characteristics and Design Guidelines
Allan Seabridge and Mohammad Radaei

UAS Integration into Civil Airspace: Policy, Regulations and Strategy
Douglas M. Marshall

Introduction to UAV Systems, Fifth Edition
Paul G. Fahlstrom, Thomas J. Gleason, Mohammad H. Sadraey

Introduction to Flight Testing
James W. Gregory, Tianshu Liu

Foundations of Space Dynamics
Ashish Tewari

Essentials of Supersonic Commercial Aircraft Conceptual Design
Egbert Torenbeek

Design of Unmanned Aerial Systems
Mohammad H. Sadraey

Future Propulsion Systems and Energy Sources in Sustainable Aviation
Saeed Farokhi

Flight Dynamics and Control of Aero and Space Vehicles
Rama K. Yedavalli

Design and Development of Aircraft Systems, 3rd Edition
Allan Seabridge, Ian Moir

Helicopter Flight Dynamics: Including a Treatment of Tiltrotor Aircraft, 3rd Edition
Gareth D. Padfield CEng, PhD, FRAeS

Space Flight Dynamics, 2nd Edition
Craig A. Kluever

Performance of the Jet Transport Airplane: Analysis Methods, Flight Operations, and Regulations
Trevor M. Young

Small Unmanned Fixed-wing Aircraft Design: A Practical Approach
Andrew J. Keane, András Sóbester, James P. Scanlan

Advanced UAV Aerodynamics, Flight Stability and Control: Novel Concepts, Theory and Applications
Pascual Marqués, Andrea Da Ronch

Differential Game Theory with Application to Missiles and Autonomous Systems Guidance
Farhan A. Faruqi

Introduction to Nonlinear Aeroelasticity
Grigorios Dimitriadis

Introduction to Aerospace Engineering with a Flight Test Perspective
Stephen Corda

Aircraft Control Allocation
Wayne Durham, Kenneth A. Bordignon, Roger Beck

Remotely Piloted Aircraft Systems: A Human Systems Integration Perspective
Nancy J. Cooke, Leah J. Rowe, Winston Bennett Jr., DeForest Q. Joralmon

Theory and Practice of Aircraft Performance
Ajoy Kumar Kundu, Mark A. Price, David Riordan

Adaptive Aeroservoelastic Control
Ashish Tewari

The Global Airline Industry, 2nd Edition
Peter Belobaba, Amedeo Odoni, Cynthia Barnhart, hristos Kassapoglou

Introduction to Aircraft Aeroelasticity and Loads, 2nd Edition
Jan R.Wright, Jonathan Edward Cooper

Theoretical and Computational Aerodynamics
Tapan K. Sengupta

Aircraft Aerodynamic Design: Geometry and Optimization
András Sóbester, Alexander I J Forrester

Stability and Control of Aircraft Systems: Introduction to Classical Feedback Control
Roy Langton

Aerospace Propulsion
T.W. Lee

Civil Avionics Systems, 2nd Edition
Ian Moir, Allan Seabridge, Malcolm Jukes

Aircraft Flight Dynamics and Control
Wayne Durham

Modelling and Managing Airport Performance
Konstantinos Zografos, Giovanni Andreatta, Amedeo Odoni

Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes
Egbert Torenbeek

Design and Analysis of Composite Structures: With Applications to Aerospace Structures, 2nd Edition
Christos Kassapoglou

Aircraft Systems Integration of Air-Launched Weapons
Keith A. Rigby

Understanding Aerodynamics: Arguing from the Real Physics
Doug McLean

Aircraft Design: A Systems Engineering Approach
Mohammad H. Sadraey

Theory of Lift: Introductory Computational Aerodynamics in MATLAB/Octave
G.D. McBain

Sense and Avoid in UAS: Research and Applications
Plamen Angelov

Morphing Aerospace Vehicles and Structures
John Valasek

Spacecraft Systems Engineering, 4th Edition
Peter Fortescue, Graham Swinerd, John Stark

Unmanned Aircraft Systems: UAVS Design, Development and Deployment
Reg Austin

Hypersonic Slender Body Aerodynamics

Ethirajan Rathakrishnan

WILEY

This edition first published 2025

Registered Office(s)
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, New Era House, 8 Oldlands Way, Bognor Regis, West Sussex, PO22 8NQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data Applied for:
Hardback: 9781394285631

Cover image: © SONGPHOL THESAKIT/Getty Image
Cover design: Wiley

Set in 9.5/12.5pt STIXTwoText by Straive, Chennai, India

This book is dedicated to my parents,
Mr. Thammanur Shunmugam Ethirajan
and
Mrs. Aandaal Ethirajan

Contents

Preface

This book is developed to serve as text for a course on *Slender Body Aerodynamics* at the introductory level course for undergraduate and graduate level.

The basic aim of this book is to make a complete text covering the basic and applied aspects of slender body aerodynamics for students, engineers, and applied physicists. The philosophy followed in this book is that the subject of aerodynamic theory is covered combining the theoretical analysis, physical features, and the application aspects.

Considerable number of solved examples are given in all the chapters to fix the concepts introduced, and large number of exercise problems along with answers are listed at the end of these chapters to test the understanding of the material studied.

The book is organized in a logical manner and the topics are discussed in a systematic way, beginning with the basic aspects and then proceeding to the involved aspects of theory and application.

The selected references given at the end are hoped to be a useful guide for further study of the voluminous subject.

This book is the outgrowth of lectures presented by the author over a number of years, both at undergraduate and graduate level. The student, or reader, is assumed to have a background in the basic courses of fluid mechanics, gas dynamics, thermodynamics, and heat transfer. Advanced undergraduate students should be able to handle the subject material comfortably. Sufficient details have been included, so that the text can be used for self study. Thus, the book can be useful for scientists and engineers working in the field of aerodynamics in industries and research laboratories.

My sincere thanks to my undergraduate and graduate students in India and abroad, who are directly and indirectly responsible for the development of this book.

I thank Dr. S. M. Aravindh Kumar, Assistant Professor, Department of Aerospace Engineering, SRM Institute of Science and Technology, for checking the manuscript and suggesting some useful changes that made the manuscript impressive.

For instructors only, a companion Solutions Manual that contains typed solutions to all the end-of-chapter problems and lecture slides for the complete book are available from the publisher.

Chennai — *Ethirajan Rathakrishnan*
January 2025

About the Author

Ethirajan Rathakrishnan is a professor of aerospace engineering at the Indian Institute of Technology Kanpur, India. He is well known internationally for his research in the area of high-speed jets. The limit for the passive control of jets, called the Rathakrishnan Limit, is his contribution to the field of jet research, and the concept of *breathing blunt nose (BBN)*, which simultaneously reduces the positive pressure at the nose and increases the low pressure at the base, is his contribution to drag reduction at hypersonic speeds. Positioning the twin-vortex Reynolds number at around 5000, by changing the geometry from cylinder, for which the maximum limit for the Reynolds number for positioning the twin-vortex was found to be around 160, by von Karman, to flat plate, is his addition to vortex flow theory. He has published a large number of research articles in many reputed international journals. He is a fellow of many professional societies including the Royal Aeronautical Society. Rathakrishnan serves as the editor-in-chief of the *International Review of Aerospace Engineering* (IREASE) and *International Review of Mechanical Engineering* (IREME) journals. He has authored the following books: *Gas Dynamics*, 7th ed. (PHI Learning, New Delhi, 2020); Fundamentals of Engineering Thermodynamics, 2nd ed. (PHI Learning, New Delhi, 2005); *Fluid Mechanics: An Introduction*, 4th ed. (PHI Learning, New Delhi, 2021); *Gas Tables*, 3rd ed. (Universities Press, Hyderabad, India, 2012); *Theory of Compressible Flows* (Maruzen Co., Ltd. Tokyo, Japan, 2008); *Gas Dynamics Work Book*, 2nd ed. (Praise Worthy Prize, Napoli, Italy, 2013); *Elements of Heat Transfer* (CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA, 2012); *Theoretical Aerodynamics* (John Wiley, New Jersey, USA, 2013); *High Enthalpy Gas Dynamics* (John Wiley & Sons Inc., 2015); *Dynamique Des Gaz* (Praise Worthy Prize, Napoli, Italy, 2015); and *Instrumentation, Measurements and Experiments in Fluids*, 2nd ed. (CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA, 2017), *Helicopter Aerodynamics*, (PHI Learning, New Delhi, 2019); *Applied Gas Dynamics* 2nd ed. (John Wiley & Sons Inc., 2019), *Introduction to Aerospace Engineering – Basic Principles of Flight* (John Wiley, New Jersey, USA, 2021), *Encyclopedia of Fluid Mechanics*

(CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA, 2022), Fluid and Thermal Dynamics Answer Bank for Engineers: The Concise Guide with Formulas and Principles for Students and Professionals (Brown Walker Press, FL, USA, 2023) and *Mind Power The Sixth Sense* (Routledge, Taylor & Francis Group, Boca Raton, Florida, USA, 2023).

Nomenclature

A	aspect ratio
a	speed of sound
ac	aerodynamic center
b	span
Btu	British thermal unit
c	chord
c_i	inner chord
c_o	outer chord
cg	center of gravity
c.p	center of pressure
C_D	drag coefficient
C_{D_L}	coefficient of drag due to lift
C_{D_f}	skin friction drag coefficient
C_f	skin friction coefficient
C_L	lift coefficient
C_M	pitching moment coefficient
C_N	normal force coefficient
C_p	coefficient of pressure
C_T	thrust coefficient
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
d	diameter
D	drag
D_f	drag due to friction
D_L	drag due to lift
dB	decibel
g_0	gravitational acceleration
h	altitude
h	height

h	specific enthalpy
H	total enthalpy
ISA	International Standard Atmosphere
K	hypersonic similarity parameter
Kn	Knudsen number
L	lift
L/D	aerodynamic efficiency
M	Mach number
M_{det}	shock detachment Mach number
M	moment
$\overline{M}$	mean molecular weight
m	molecular mass of air
n	number of degree of freedom
p	pressure
p_0	stagnation pressure
q	dynamic pressure ($\frac{1}{2}\rho V^2$)
q	source strength/length
$\overline{q_F}$	average rate at which heat is transferred to the nose per unit frontal area of the body
q_r	surface radiative heat flux
R	gas constant
R_c	radius of curvature
R_u	universal gas constant
$\mathrm{R_e}$	Reynolds number
s	span
S	wing area
S_{base}	base area (reference area)
S_{wet}	wetted area
St_o	Stanton number
T	temperature
T_0	stagnation temperature
t	time
V	velocity
$\mathbf{V}$	volume
$\overline{\mathbf{V}}$	nondimensionalized volume
u	perturbation velocity along the flow direction
u_g	normal component of velocity at any point on the body contour
v	perturbation velocity in the transverse direction
v_n	velocity component normal to the contour
w	perturbation velocity in the normal direction
x	flow direction

y	transverse direction
z	normal direction
z	compressibility factor

Greek symbols

α	angle of attack
α_{local}	local angle of attack
α	energy-accommodation coefficient
β	shock angle
Δ	"the change in"
ϵ	density ratio
ϵ	surface emissivity
Λ	leading-edge angle
λ	mean free path
λ_{eff}	slenderness ratio
Γ	circulation
γ	isentropic index
γ	specific heats ratio
γ	vorticity distribution
μ	viscosity coefficient
∇	total flux change
ν	Prandtl–Meyer function
Ω	angular velocity
Φ	velocity potential function
ϕ	perturbation velocity potential function
ϕ	shape correction factor
ρ	density
$\sigma(x)$	slope of shock
τ	volume parameter
$\overline{\tau_m}$	nondimensional thickness for the wing
θ	nose angle
θ	flow turning angle

Subscripts

0	stagnation state
∞	freestream
w	wall